Presentation content partially taken from AIAA Space 2007 Orbital Express Mission Summary by Bob Friend/Advanced Systems

Future Space Robotics and Large Optical Systems:

A Picture of Orbital Express

Ares V Workshop
27 April 2008

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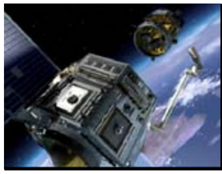

Orbital Express Overview

- Orbital Express (OE) Demonstration System demonstrated the technical feasibility, operational utility, and cost effectiveness of autonomous techniques for on-orbit satellite servicing

- The specific objectives of OE were to develop and demonstrate on orbit:
  - A nonproprietary satellite servicing interface specification
  - Orbit propellant transfer between a depot/serviceable satellite and a servicing satellite
  - Component transfer and verified operation of the component
  - Autonomous rendezvous, proximity operations, and capture

- On-Orbit demonstration of technologies is required to support autonomous on-orbit servicing of satellites
  - Perform autonomous fuel transfer
    - Transfer of propellant in a 0-g environment
  - Perform autonomous ORU transfer
    - Component replacement
      - Battery Transfer
      - Computer Transfer
  - Perform autonomous rendezvous and capture of a client satellite
    - Direct Capture
    - Free-Flyer Capture

http://www.boeing.com/ids/advanced_systems/orbital/pdf/orbital_express_demosys_03.pdf

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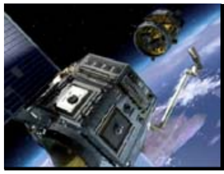


Orbital Express Mission Objectives And Scenarios

- Overarching Orbital Express objective is to Demonstrate technical feasibility of autonomous, on-orbit satellite servicing
- This and five subordinate objectives decomposed to 23 Mission Success Requirements, 26 mission success goals
- A total of 8 scenarios were performed, including End of Life
  - **15 Propellant transfers from commodity spacecraft and to client**
  - **7 Battery Transfers**
  - **1 Computer Transfer**
  - **6 Rendezvous and 5 Capture operations- 3 Direct, 2 Free Flyer**

General Information

- Orbital Express
  - Orbit: 492-km circular 46-deg inclination
- ASTRO
  - Dimensions:175x177cm, span 559cm
  - Power: 1560 watts
  - On-orbit fueled weight: ~1100kg
- NEXTSat:
  - Dimensions: 98cm long
  - Power: 500 watts
  - Mass: 224 kg

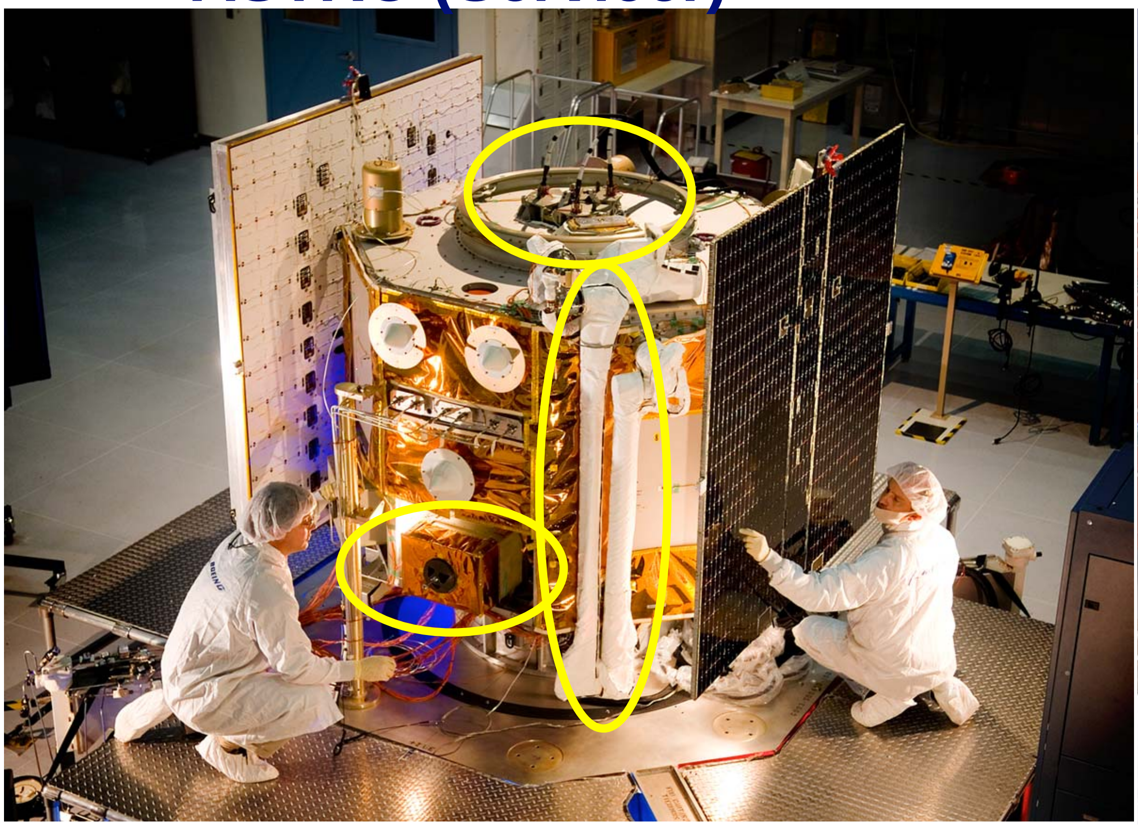
March 8, 2007
OE Launch from Cape Canaveral

http://boeingmedia.com/imageDetail.cfm?id=14750
http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=space&id=news/aw060506p1.xml

Orbital Express Vehicles

ASTRO: Autonomous Space Transfer and Robotic Orbiter
NEXTSat/CSC: Next Generation Satellite/Commodity Spacecraft

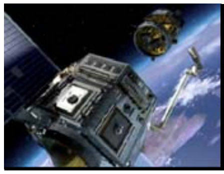
ASTRO (Servicer)



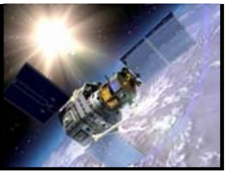
14 April 2006

NEXTSat (Client)

1 Dec. 2005



ASTRO Spacecraft Summary



- ASTRO
  - Hydrazine monopropellant reaction control system for 6 DoF Control
  - Integrated GPS and INS
  - Active servicing functions
    - Rendezvous and Proximity Operations Sensors
    - Relative Navigation Software
    - Robotic Arm
    - Active Capture Mechanism
    - Active Fluid Coupler and Fluid Transfer Components
    - Battery and Computer ORU bays
    - 1553 Data Interface
    - Crosslink

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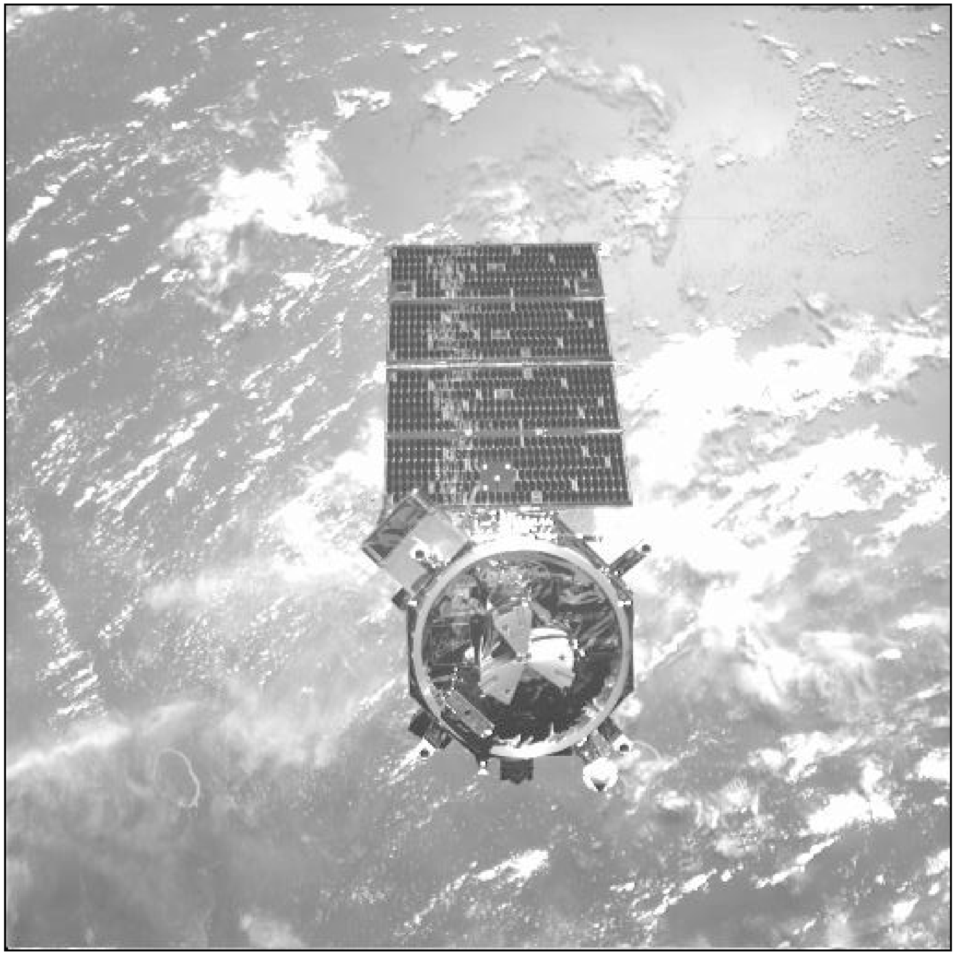
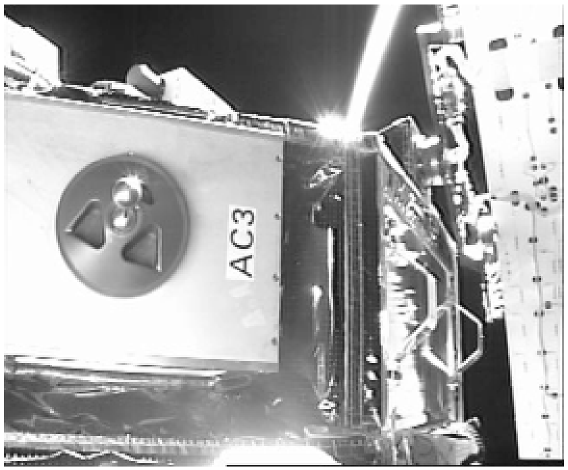
NextSat Spacecraft Summary

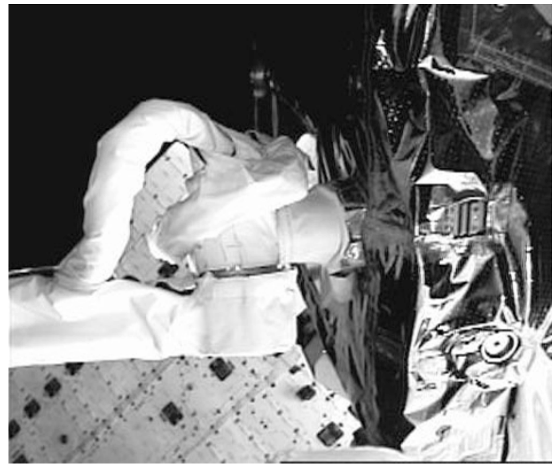


- NEXTSat/CSC
  - Next Generation Satellite/Commodities Spacecraft
  - Attitude Determination and Control, no maneuver capability
  - Fixed Solar Array
  - Standard servicing interfaces
    - Passive capture mechanism
    - Passive Fluid Coupler and Transfer Tank
    - Battery ORU bay
    - 1553 Data Interface
    - Crosslink

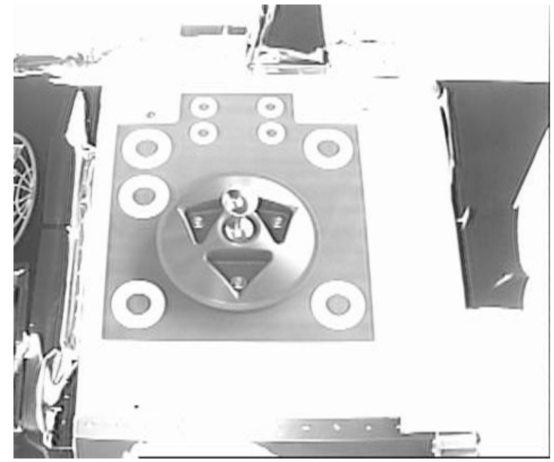
Robotic Servicing Components



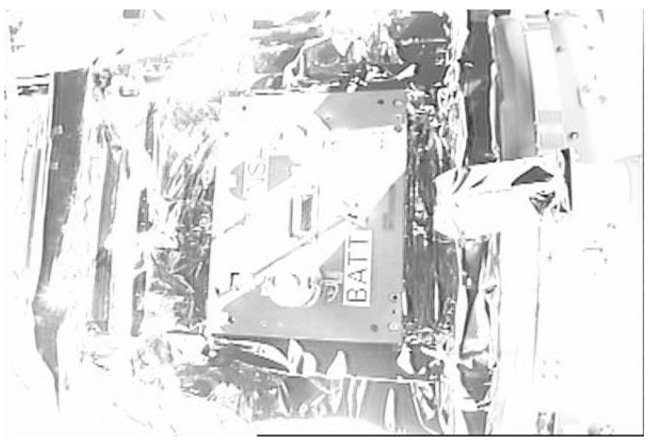
AC3 Computer ORU



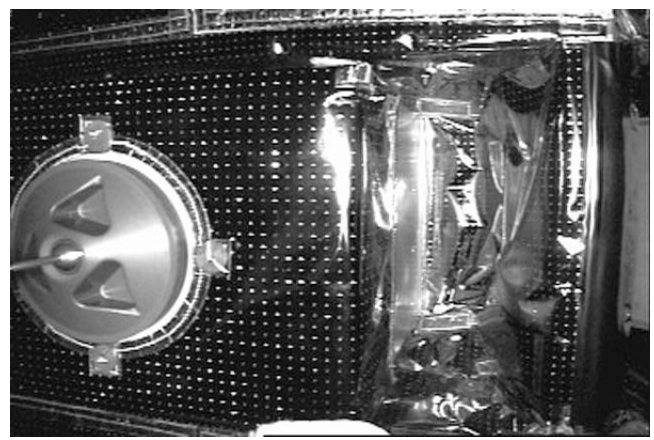
Arm Shoulder Joint



NEXTSat Grapple Fixture



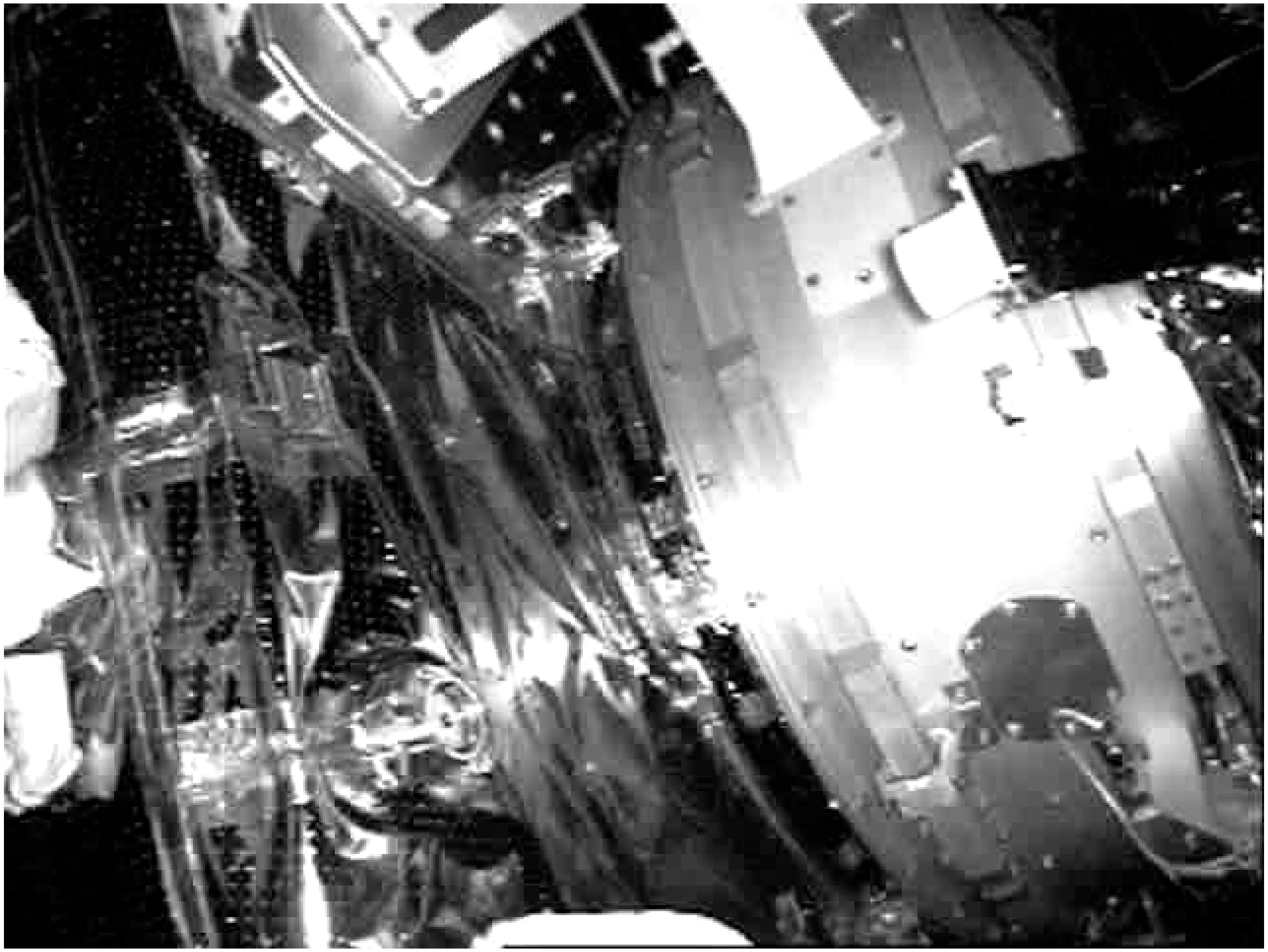
Battery ORU Interface



Battery ORU

http://www.darpa.gov/orbitalexpress/mission_updates.html

On-Orbit Mated Global Video Survey



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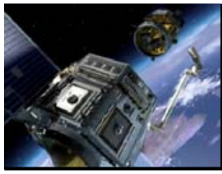
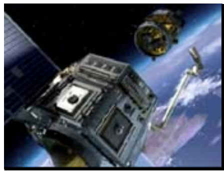


Experiment Summary- Propellant Transfers

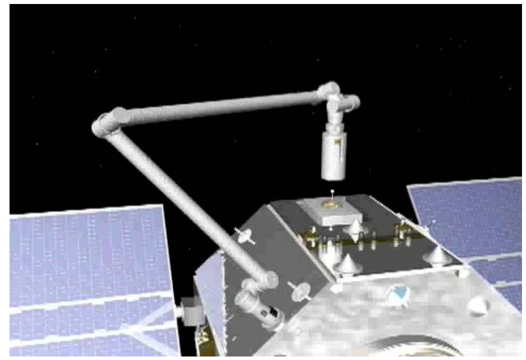
- The Northrop Grumman-provided hardware demonstrates autonomous transfer of hydrazine propellant to and from the NextSat spacecraft, in addition to providing the propulsion needed for six-degree-of-freedom vehicle control.
- Multiple types of fuel transfers are demonstrated
- Total of 15 propellant transfers performed
  - 2 at lowest level of autonomy
  - 7 at middle level of autonomy
  - 6 at highest level of autonomy
- Demonstration plan set a foundation for the operational system
  - Transfer from commodity station performed
  - Transfer to client satellite performed
- Capability leads to the autonomous replenishment of fuel to existing satellites, allowing more flexibility and extension of life

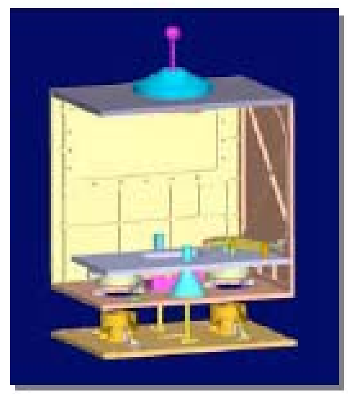
End-to-End Test



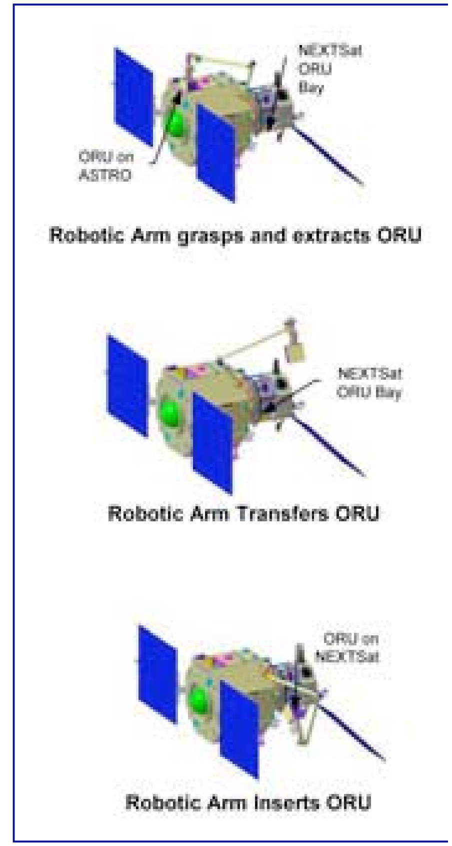
Experiment Summary- ORU Transfers

- Standard interfaces for all ORUs
  - Boeing: ASTRO interface
  - Ball: NEXTSat interface
  - MDA: ORU interface
- Transfer two types of components
  - Batteries
  - Computers
- Demonstration plan set a foundation for the operational system
  - Total of 8 battery & computer transfers performed
    - 1 at lowest autonomy, 2 at middle, and 6 at highest level of autonomy
  - Transfers to client and from commodity station completed





ORU



On-Orbit ORU Transfer Video

ORU Transfer Interfaces
Video Link

http://www.darpa.gov/orbitalexpress/mission_updates.html

Experiment Summary- Unmated Operations

- Autonomous Guidance, Navigation, & Control
  - Autonomous GNC software performs demate, separation, departure, rendezvous, proximity operations, and capture
  - Fully-autonomous attitude software points vehicle in require directions during each segment of approach and separation
  - Onboard guidance sequencer progresses through translation and pointing modes during approach and separation
  - Functionally redundant sensors proven to track target from over 500 km to capture
  - Fully-autonomous navigation filters sort and weight data from multiple sources
  - GN&C performs internal sanity checks and executes rendezvous abort if thresholds exceeded

OE Rendezvous GN&C system is capable of autonomous rendezvous from >500 km to capture

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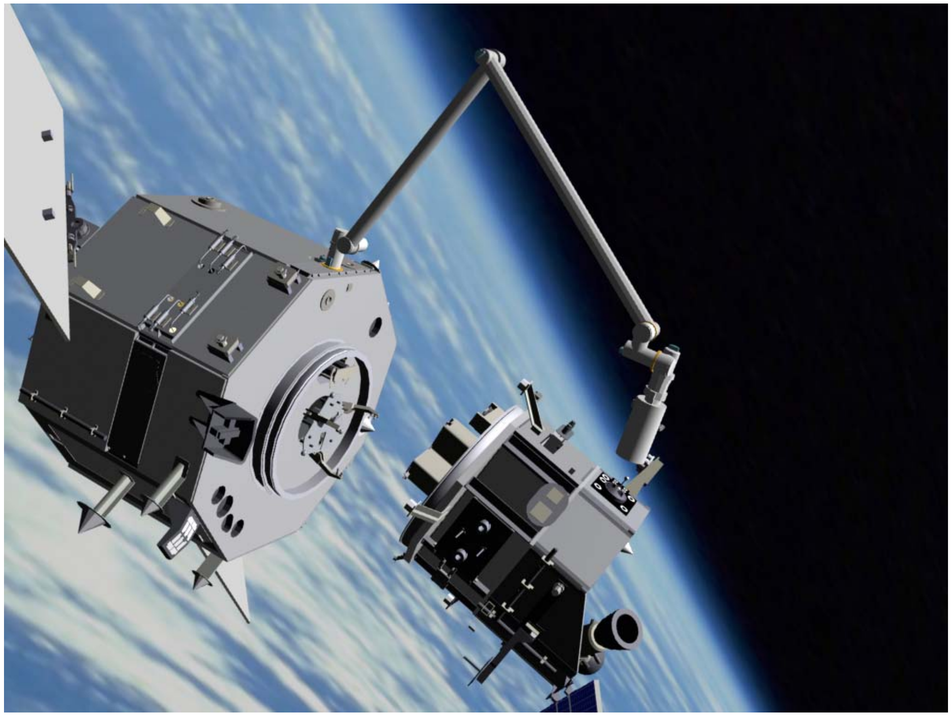
On-Orbit 4km Unmated Video

Advanced Networks & Space Systems

Scenario 7-1:
4 km separation
demonstration conducted
June 22
Video Link

http://www.darpa.gov/orbitalexpress/mission_updates.html

Free-Flyer Capture & Berthing



- Robotic Arm on ASTRO will drive autonomously using highly-reliable vision feedback from a camera at its tip to capture NEXTSat
- Berthing requires the advanced robotic arm to grapple NEXTSat from a distance of 1.5 m and position it within the capture envelope

Visual Servo/FFC & Release Video Link

Berthing Video Link

http://www.boeing.com/ids/advanced_systems/orbital/oe_mm/index.html
http://www.darpa.gov/orbitalexpress/mission_updates.html
http://www.boeing.com/ids/advanced_systems/orbital/pdf/orbital_express_demosys_18.pdf
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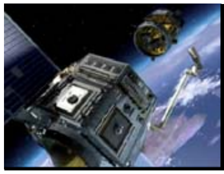
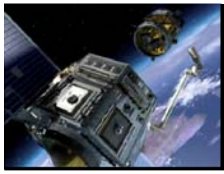


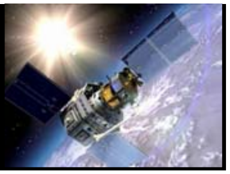
Autonomous Operations

- Autonomy
  - Design accommodates four levels of supervised autonomy, and demonstrates servicing operations under increasingly challenging levels
  - Autonomous controllers use man-machine collaborative autonomy, enabling variable level autonomy implementation
- Autonomous Mission Manager
  - Implements operations requirements by using sequences and related information in a database
    - Ability to plan missions dynamically
    - Command subsystems within the vehicle management system
    - Monitor systems and diagnose their failures
  - Database executed fully autonomously, but with high level of input from ground team into database creation
  - Controls starting, interruption, managing Authority-To-Proceeds and aborts
- Ground Segment
  - Assemble and verify sequences for upload
  - Displays status of Mission Manager and next planned event

Mission Support Team KAFB, NM



Major World Firsts Accomplished



- Six Major World and US Firsts
  - **First US fully autonomous Propellant (Hydrazine) transfer**
  - **First fully aut**
  - **rget**
  - **ve**
  - **Long Range (>400k**

♣100% Mission Success

Requirements Met (23/23)

♣96% of goals met (25 of 26)

- Very positive DARPA Comments Received
  - **"The folks who did this clearly have more experience in how to bring two spacecraft together than probably anyone in the world--past and present. Thanks again to everyone." Dr. Tony Tether 5/19/07**
  - **"OE has done things that no space mission has ever before attempted. We were successful because of your professional competence, creativity, sheer stubbornness, and an overwhelming desire to see it through." Lt. Col. Fred G. Kennedy, DARPA Program Manager, 7/23/07**

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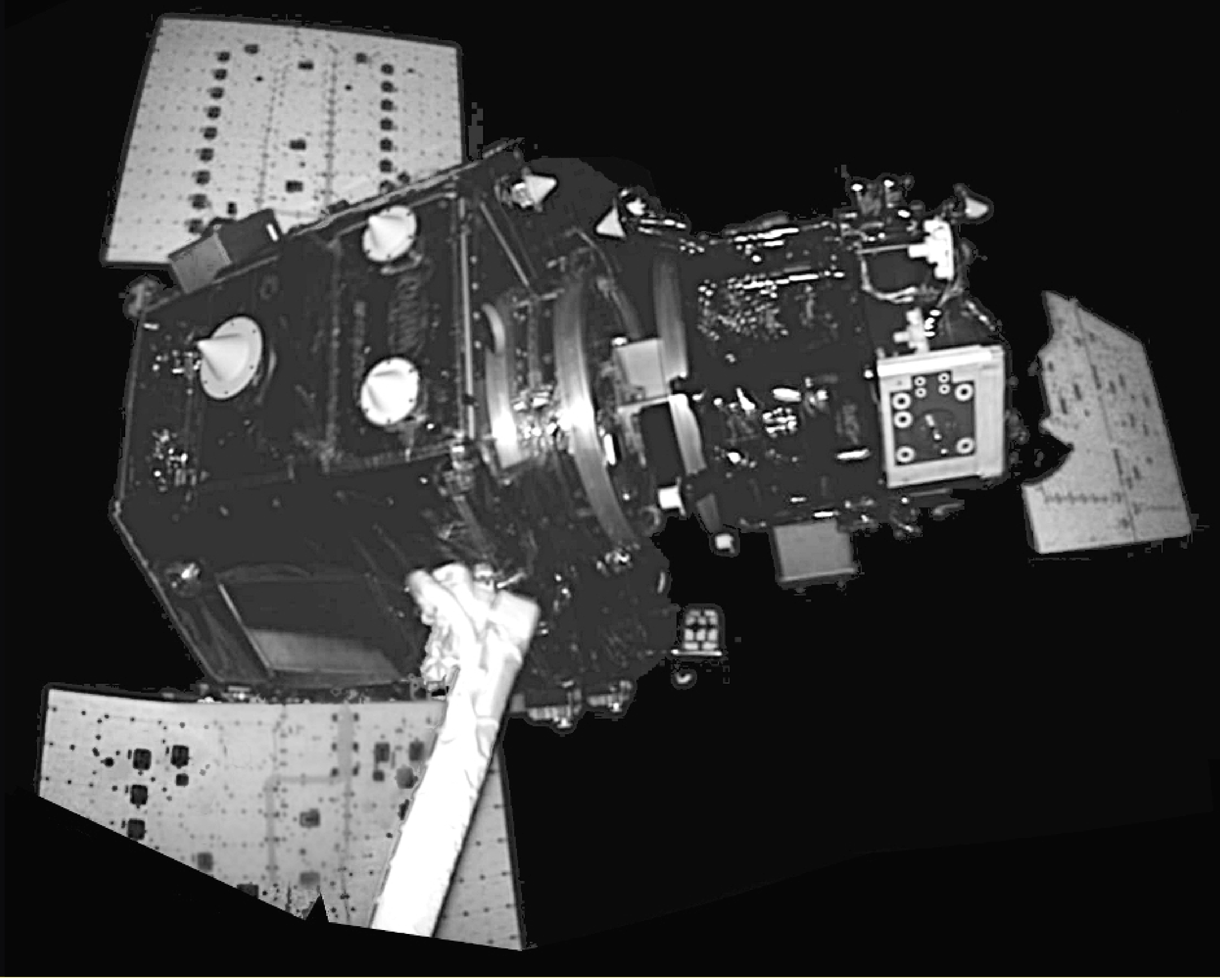
Orbital Express Self Portrait



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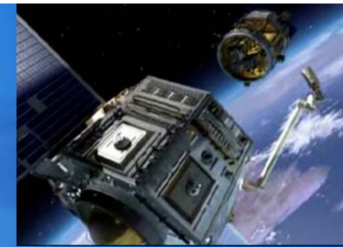
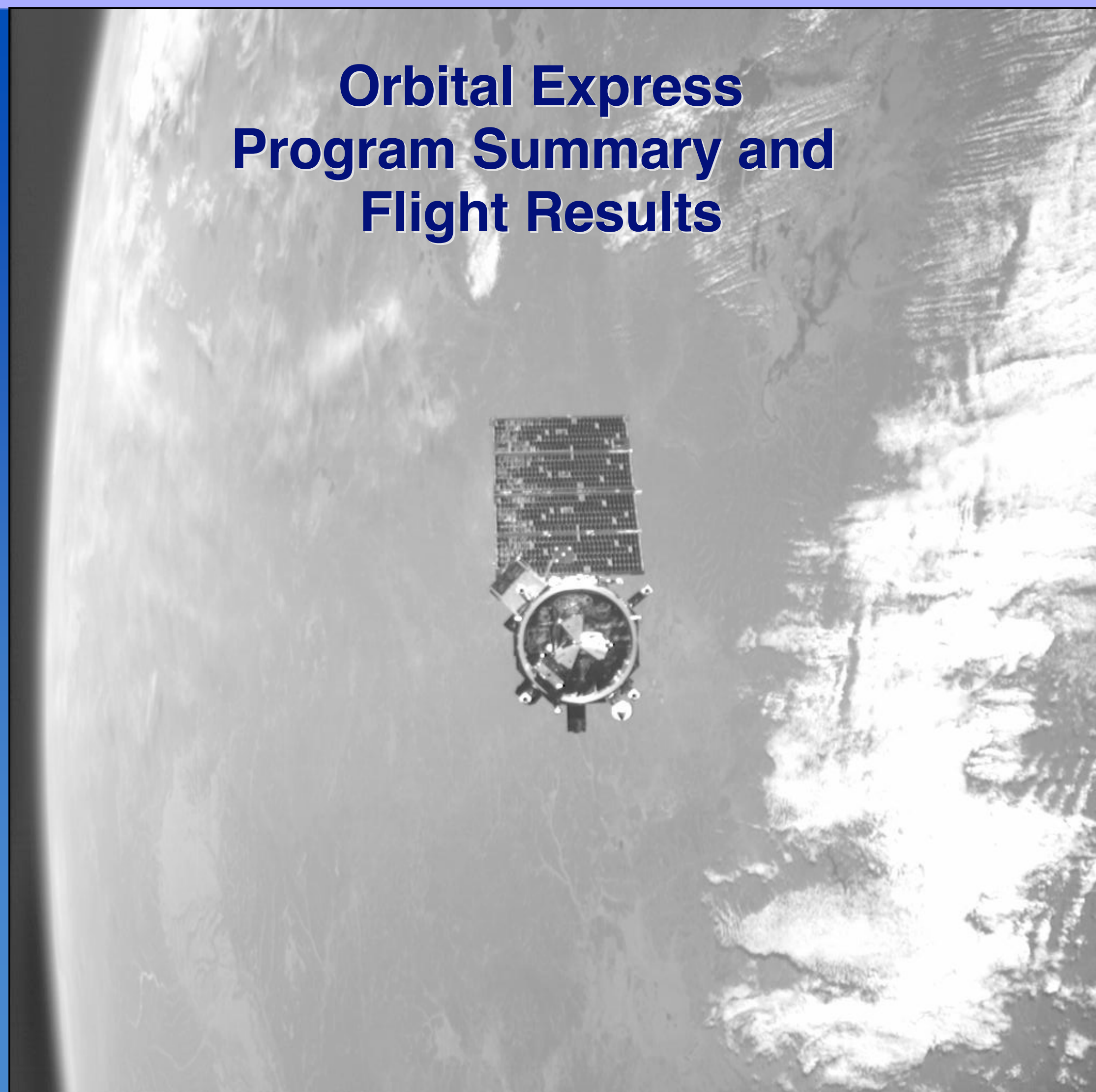
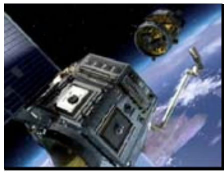
Back Up

AIAA Space 2007 Orbital Express Summary Presentation - External

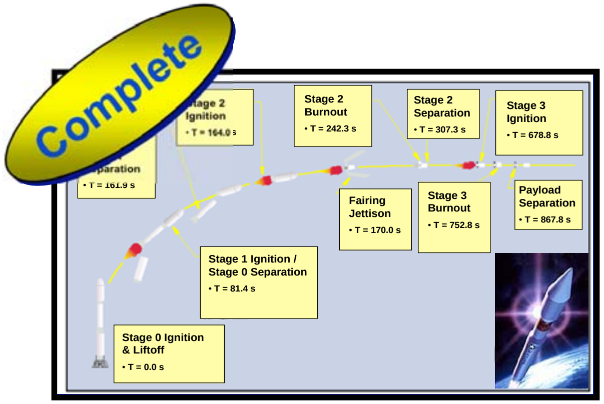


Orbital Express Program Summary and Flight Results

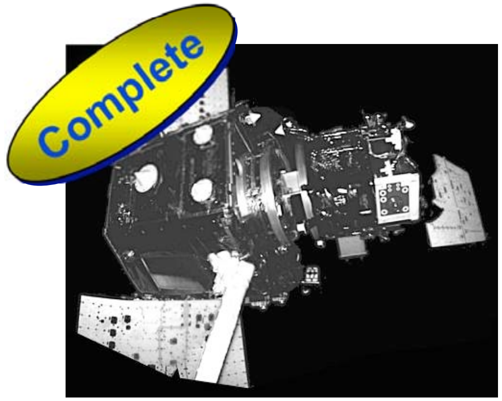




On-Orbit Mission Phases



1. Launch & Activation

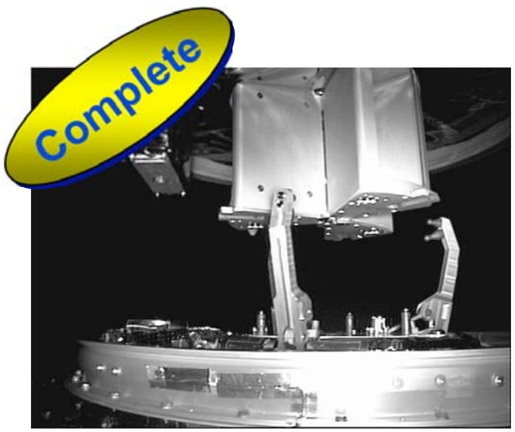


2. Checkout ASTRO & NEXTSat

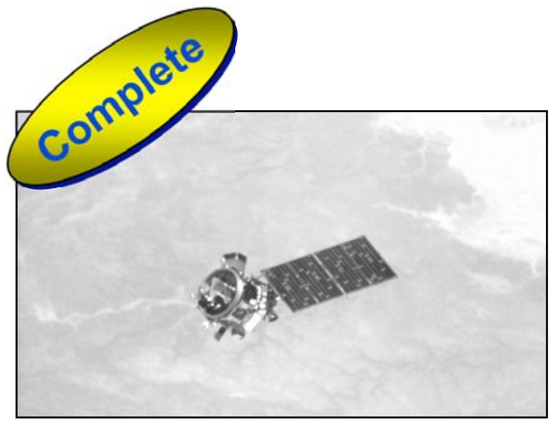
Fuel

ORU

3. 1st Fuel & ORU Transfers



4. Eject Separation Ring; Sensor Testing; Additional Fuel and ORU Transfers



5. Perform Prox Ops ≤120m

6. Rendezvous up to 7km; Integrated Rendezvous, ORU and Fuel Transfers

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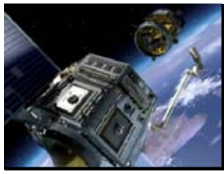


Top Level Summary

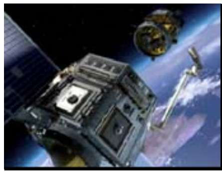
- A total of 9 Scenarios planned- 2 Mated and 7 Unmated demonstrations, 7 were executed
  - Second Unmated exercise satisfied criteria for 3 of the unmated exercises
- Fuel expenditure lower than predicted
  - Prior to end-of-life exercise, ASTRO had 127 of 144 kg usable fuel remaining (88%)
  - After end-of-life exercise, but prior to decommissioning, ASTRO had 98 kg usable fuel remaining (68%)
  - After decommissioning, ASTRO had 0 kg usable fuel remaining
- Mission had its share of problems
  - Some hardware, mostly software
  - Each resolved by OE ground team
  - Both vehicles healthy prior to decommissioning
- Several firsts in autonomous operations
- Numerous lessons learned from things that went right & things that went wrong
- Total mission success – all mated & unmated objectives met

Launch and Activation

9 Mar 2007 (UTC)

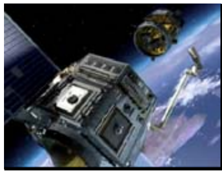
Launch and Activation

- Successful Launch on ATLAS V on March 8 at 10:10 EST
- ASTRO/NEXTSat separation from LV
- Successful avionics initialization, solar array deployment
- Held attitude on RCS while SIGI initialization process started
  - SIGI Initialization failed, putting ASTRO into Sun Safe and RWA control
- Immediately upon entering sun safe, ASTRO went unstable
  - Pitch axis RWA had incorrect sign in vehicle software
- Ground intervened and moded ASTRO to RCS control while investigating RWA and SIGI issues
- RWA sign problem fixed through upload of an I-load parameter correcting sign
- Re-initialization of the SIGI was attempted
  - SIGI initialized and ground commanded ASTRO into Nominal Sun Track mode
  - Ground did not notice SIGI had initialized improperly
    - Resulted in steering ASTRO and NextSat away from the sun
    - Communication also lost because antenna manager software was using incorrect attitude data



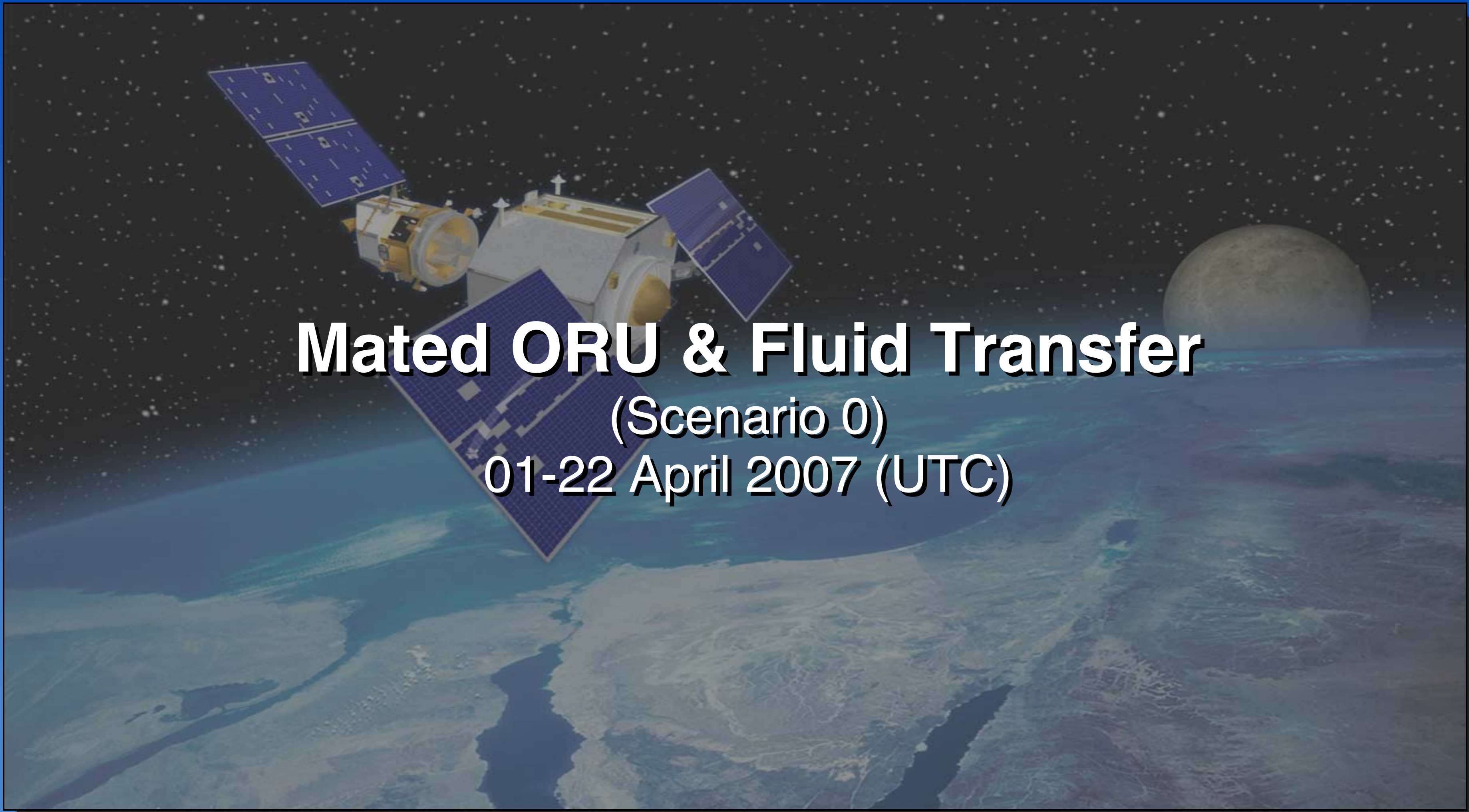
Launch Anomaly Recovery

- Several hours passed with no comm
  - Got 1 short AFSCN contact and commanded ASTRO to Free Drift
    - Hope was that it would drift to the sun
    - Power was critical at that point (<26 volts)
  - No improvement in vehicle state noted
    - Still off sun, Bus voltage 22 volts and dropping
- As last ditch resort decided to try control stack using NextSat
  - NextSat was also power critical
  - 1 contact available
    - Short contact (8 minutes)
  - Determined what was required to attempt
    - Disabled all NextSat fault protection
    - Forced NextSat to believe it was Unmated
    - NextSat then maneuvered the stack to Solar Inertial attitude
- Operation completed successfully, saved the mission



Launch Anomaly Recovery (cont'd)

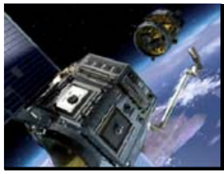
- While power and thermal balance recovered, Anomaly Resolution Tiger Team:
  - Verified health & status
  - Systematically looked at data
  - Recreated configuration and events in the SIL
  - Determined root cause of the problems
  - Developed solutions and checked them out in the SIL
- Successfully implemented the solutions with a flight SW upload and returned stack control to ASTRO
- All GNC subsystems returned to nominal by 3/15
- While investigating launch day anomalies team continued to activate and check out experiment subsystems
  - All other subsystems on both spacecraft checked out nominal
    - Checkouts completed 3/30
  - OEDMS (manipulator arm) deployed and checked out, completed mated survey
- Demonstration Scenario Operations started 04/01/07



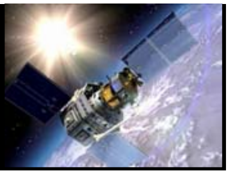
Mated ORU & Fluid Transfer

(Scenario 0)

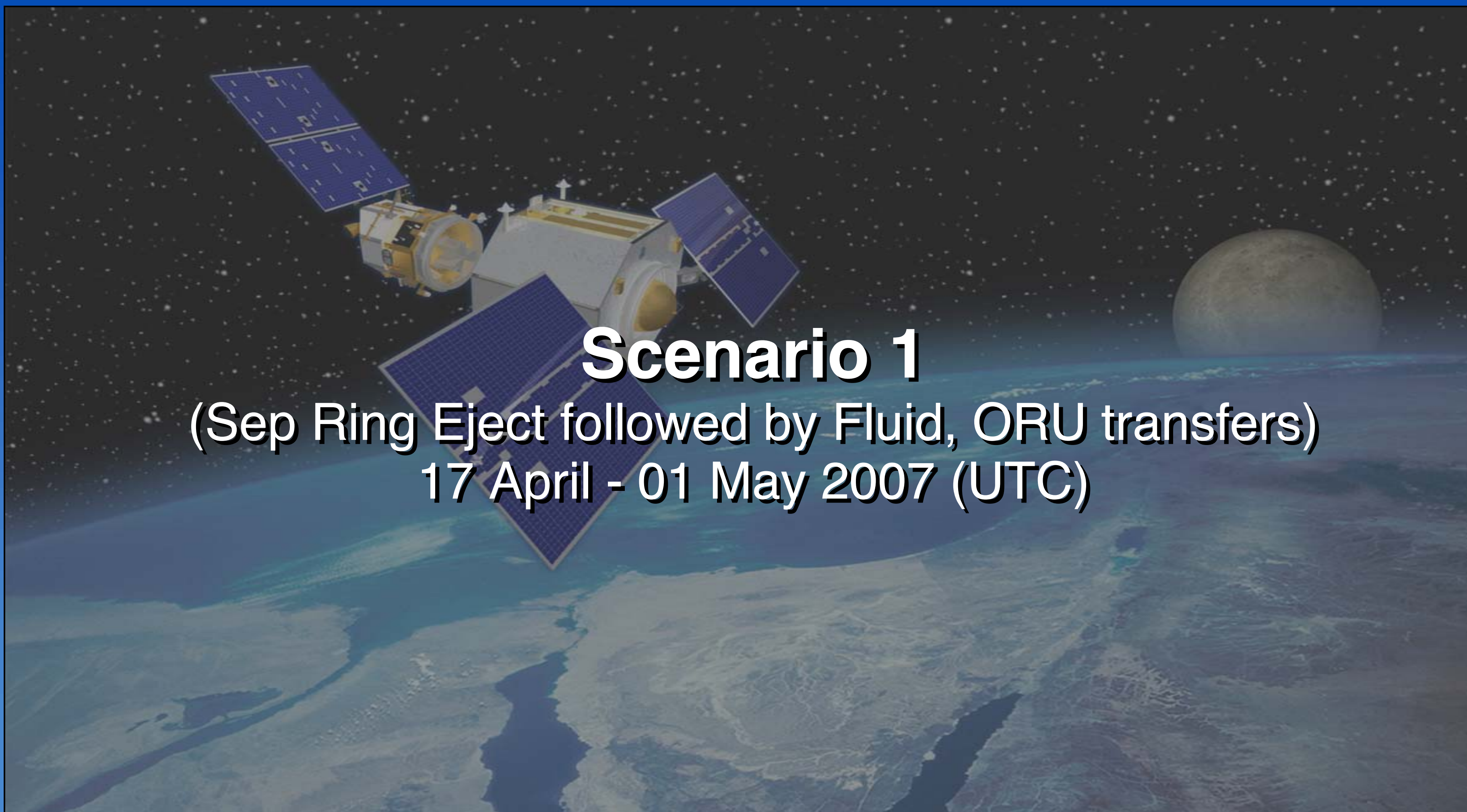
01-22 April 2007 (UTC)



Scenario 0



- Scenario 0 comprised of 11 components, referred to as Scenarios 0-1 through 0-11
  - Eight propellant transfers performed vs 9 planned
    - Two types of transfers performed
      - Ullage recompression
      - Pump Transfer
    - Scenario 0-7 skipped to resolve a pump current issue
      - Objectives accomplished during later transfers
    - Transfers to client and from commodity spacecraft (to ASTRO) performed
    - Transfers performed both before Sep ring ejection and after Sep ring ejection
  - Battery transfer performed
    - ORU battery transferred from ASTRO to NextSat
      - Successfully incorporated into the NextSat EPS



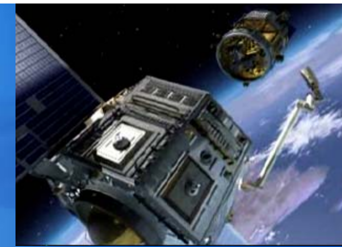
Scenario 1

(Sep Ring Eject followed by Fluid, ORU transfers)

17 April - 01 May 2007 (UTC)

Scenario 1

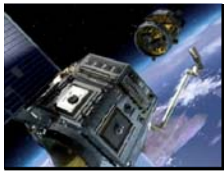
- Scenario 1 comprised of 7 components, referred to as Scenarios 1-1 through 1-7
  - Scenario 1-1 was ejection of the Sep Ring which reacted launch loads and had been between ASTRO and NS since launch
    - Covers on Sep ring covered all of the ASTRO rendezvous sensors
    - Anomaly experienced with OEDMS caused delay of ARCSS system checkout
      - ARCSS Checkout performed 4/26/07
      - Characterized sensor performance prior to first unmated operation
      - Repeatability of system mechanical alignments after unmate/mate operations
  - Scenarios 1-2 & 3 performed without any issues
    - Transferred ORU battery to ASTRO
      - Demonstrated ability to transfer from Commodity spacecraft & maintain on ASTRO
    - Transferred ORU from ASTRO back to NextSat in prep for first Unmated activity
  - Scenario 1-5 was RCS dynamic checkout
    - Verified flex interaction issues adequately addressed
  - Remainder of scenarios were propellant transfer and coupler mate/demate operations
    - Some postponed to avoid conflicting with planning and operations for first unmated scenario



Scenario 2

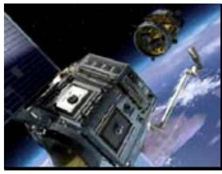
(Unmated Operation followed by propellant transfers)

05-09 May 2007 (UTC)



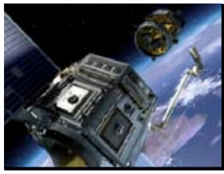
Scenario 2

- Scenario 2 comprised of 3 components, Scenarios 2-1 through 2-3
  - Scenario 2-1 was the first unmated operation
  - Followed discretely by two propellant transfers (2-2 and 2-3)
    - Used A side pump
      - Previous transfers used B side pump
      - A side pump used due to current increase issues seen in previous transfer operations
- All operations performed without anomalies



Scenario 2-1 Unmated Operations Plan

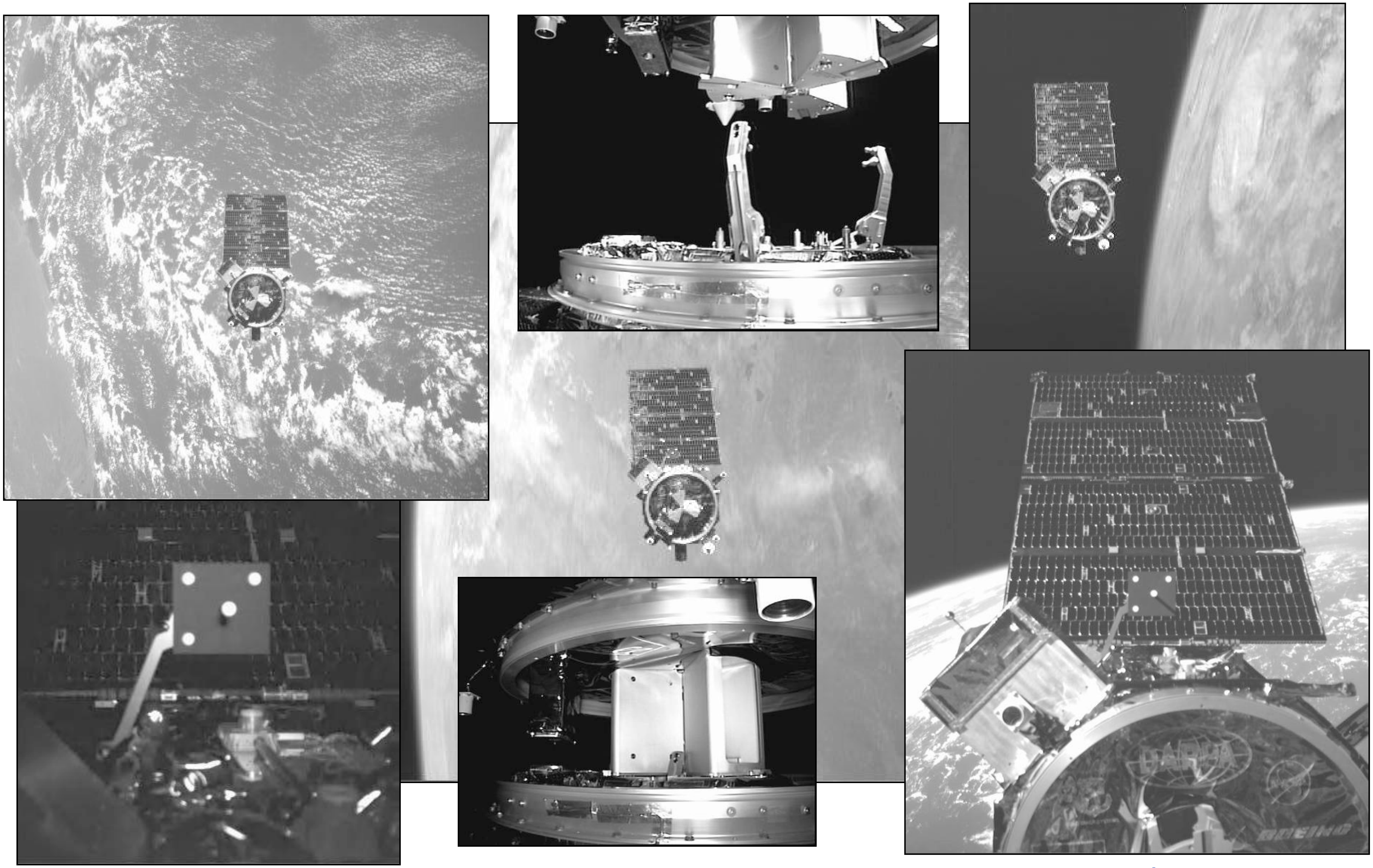
- First U.S. demonstration of autonomous rendezvous & capture (AR&C)
  - World's first AR&C without target vehicle transmitting its navigation data
- Fully separate ASTRO from NEXTSat for the first time
- Max range = 12 m
- Unmated $1^{h}\,53^{m}\,29^{s}$ within $\pm 5^{m}$
  - Night demate over COOK AFSCN
  - Separation to 10 meter stationkeep
  - Night direct capture & mate over BOSS
- Instructions preloaded at demate minus 4 hours
  - Ground hands-off until operation complete with vehicles mated & returned to solar inertial attitude
  - Onboard subsystem monitoring – and abort commanding, if needed
  - Ground subsystem monitoring – and backup abort commanding, if needed
- Redundant, dissimilar rendezvous sensors
  - Boeing passive camera-based tracking (Vis-STAR)
  - NASA-MSFC laser-based Advanced Video Guidance Sensor (AVGS)

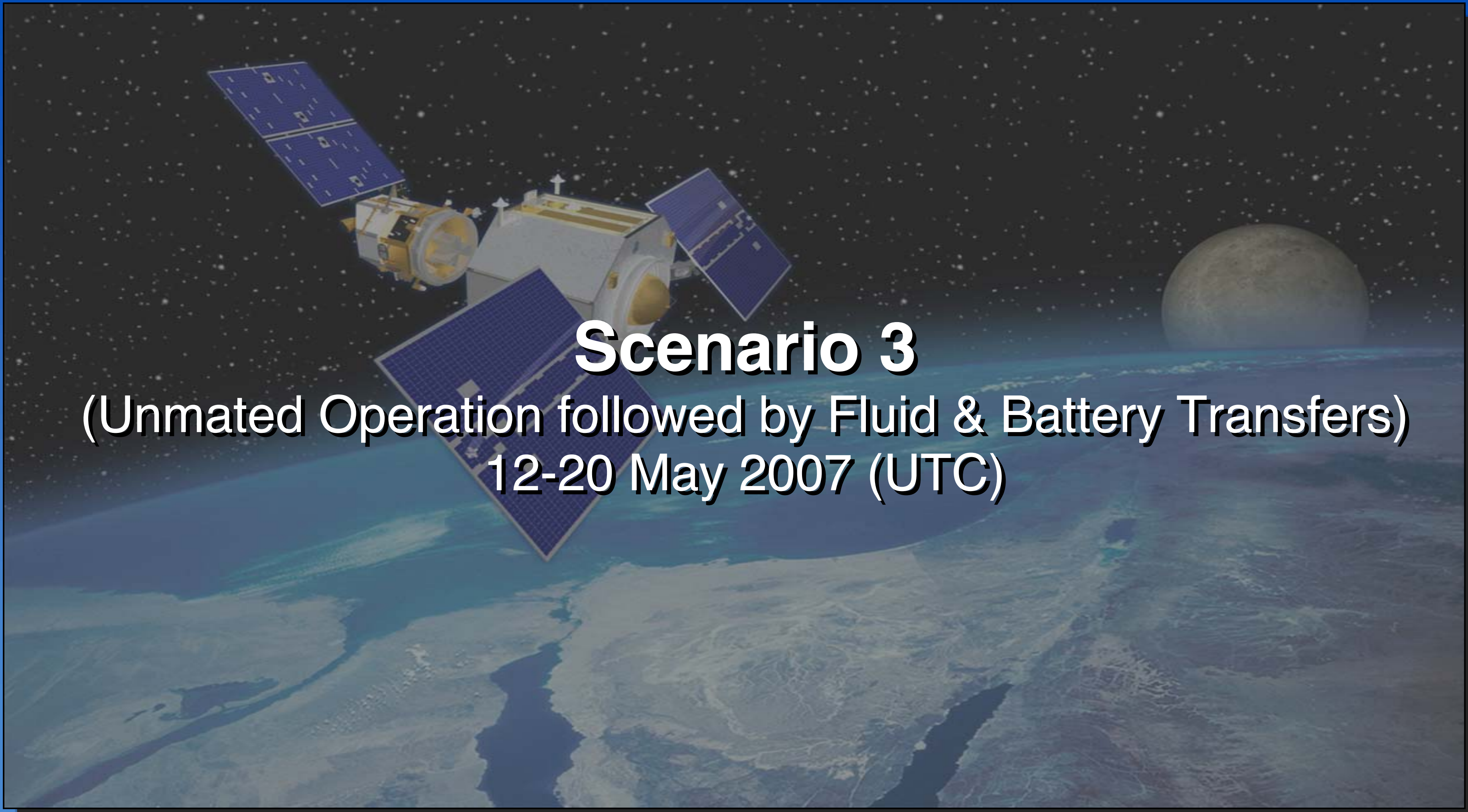


Scenario 2-1 Results

- 100% success
  - Fully autonomous, ground hands-off entire time
  - World's first AR&C without target vehicle assistance
- Max range = 12 m
- Unmated for $1^{h}\,57^{m}\,5^{s}$
  - Demate (UTC): May 6th at $5^{h}\,22^{m}\,36^{s}$
  - Capture initiation: May 6th at $7^{h}\,17^{m}\,51^{s}$
  - Mate: May 6th at $7^{h}\,19^{m}\,41^{s}$
- Mixed sensor performance
  - Wide FOV visible camera tracked inside 2 m & beyond 9 m (daylight), but not in between
  - IR camera provided good angle data but not attitude
  - AVGS continuous track entire time
- GN&C & Propulsion behaved well
- NEXTSat maintained good-to-excellent solar inertial attitude

AR&C Exercise #1 Photos

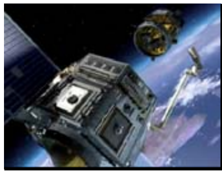




Scenario 3

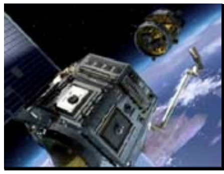
(Unmated Operation followed by Fluid & Battery Transfers)

12-20 May 2007 (UTC)



Scenario 3

- Scenario 3 comprised 3 components, Scenarios 3-1 through 3-3
  - Scenario 3-1 planned departure to 30 meters and return
    - Perform first Free Flyer capture
    - Exercise new sensor modes at further ranges
    - Evaluate sensor thresholding changes made after Scenario 2-1
  - Scenario 3-2 Battery transfer to ASTRO, Propellant transfer to NextSat
  - Scenario 3-3 Battery transfer to NextSat, Propellant transfer to ASTRO
- Scenario 3-1 experienced serious anomaly
  - Loss of sensor computer
- Scenarios 3-2 and 3-3 executed (successfully) as planned

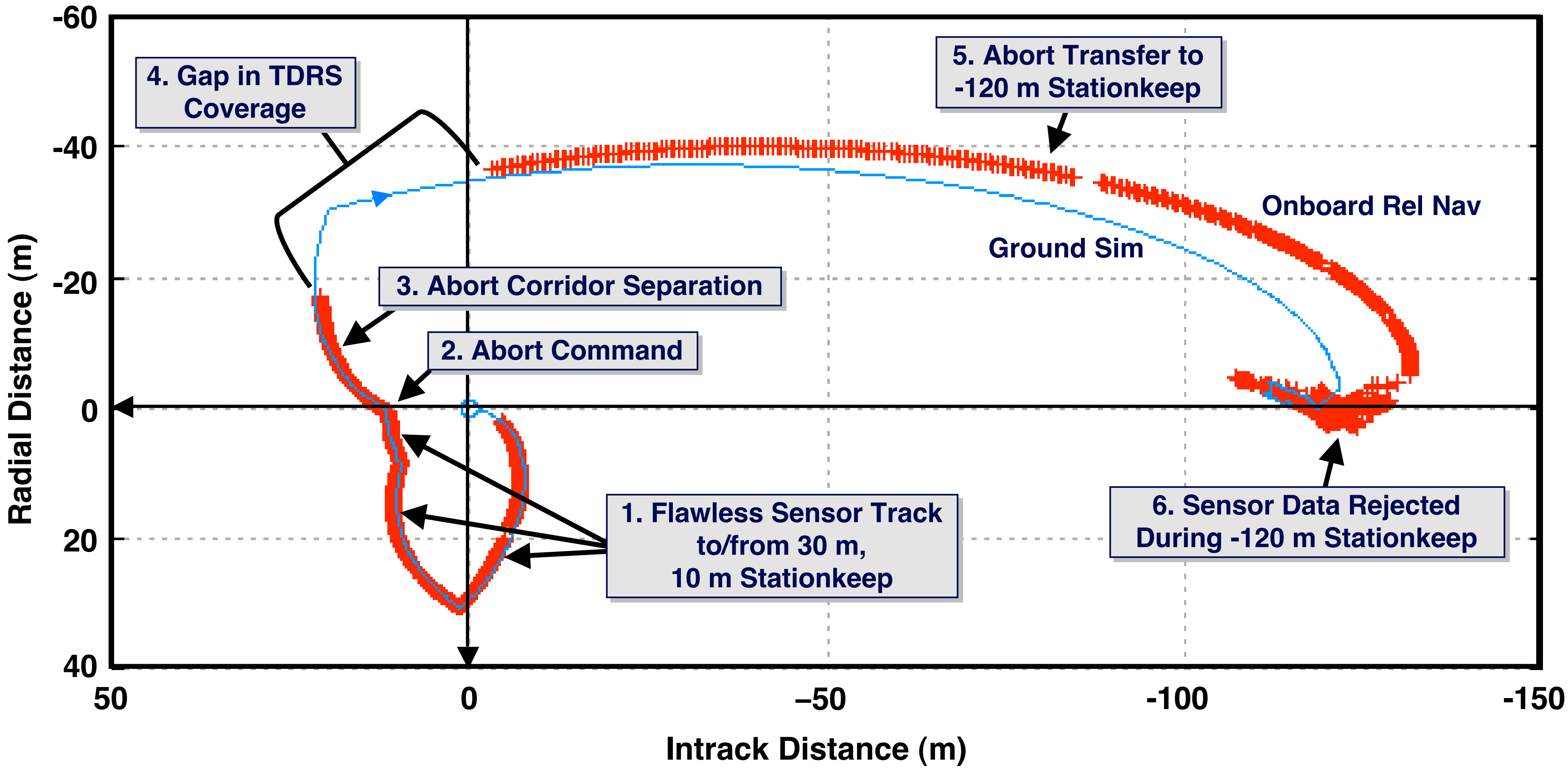


Scenario 3-1 Plan

- Max range = 30 m
- Unmated for $2^{h}\ 8^{m}\ 16^{s}$ within $\pm 5^{m}$
  - Night demate over COOK
  - Separate to 30 m
  - Approach to 10 m stationkeep
  - Final approach
- First autonomous robotic grapple & berth
  - Night pass over BOSS
- Updated camera sensor inputs

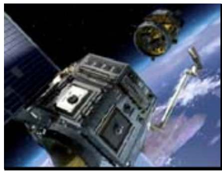
Exercise #2
Nominal & Abort Trajectory

Trajectory to -120 m Stationkeep



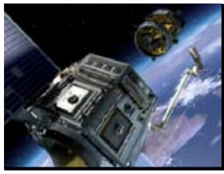
Scenario 3-1 Results

- Max range = 6 km
- Unmated for $7^{d}\ 22^{h}\ 25^{m}\ 30^{s}$
  - Demate (UTC): May 12th at $4^{h}\ 28^{m}\ 52^{s}$
  - Capture initiation: May 20th at $2^{h}\ 52^{m}\ 30^{s}$
  - Mate: May 20th at $2^{h}\ 54^{m}\ 22^{s}$
- Flawless separation to 30 m, return to 10 m, initial stationkeep
  - Camera continuous track
  - AVGS continuous track
- Sensor computer processor failed during 10 m stationkeep
  - Mission manager correctly commanded abort
  - Guidance executed flawless collision avoidance separation to 35 m, transfer to –120 m on NEXTSat v-bar (behind NEXTSat), stationkeep
  - As expected, AVGS continued track until short distance outside corridor
    - 30° off centerline
    - 45 m range



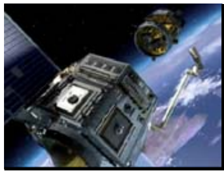
Scenario 3-1 Recovery

- During transfer, ground unable to recover sensor computer, ground booted backup computer, recovered camera tracking
- During –120 m stationkeep, Kalman filter rejected IR camera data
- Without sensor inputs, ground commanded guidance to coast & observed safe opening rate behind NEXTSat
- ASTRO coasted overnight to –2.4 km while Air Force tracked NEXTSat using PRN ranging
- Ground commanded single-pulse retrograde “nudge” burn to null opening rate, $\Delta v = -.01, 0, 0$ m/s
  - Resulted in large erroneous burn, $\Delta v = -.06, .14, .37$ m/s
  - Problem later traced to SIGI accumulated velocities added to guidance solution (diagnosed, fixed, & flight-tested prior to next exercise)
- Ground eventually determined ASTRO given fast closing rate
  - PRN ranging
  - NEXTSat appeared as disk in narrow FOV visible camera

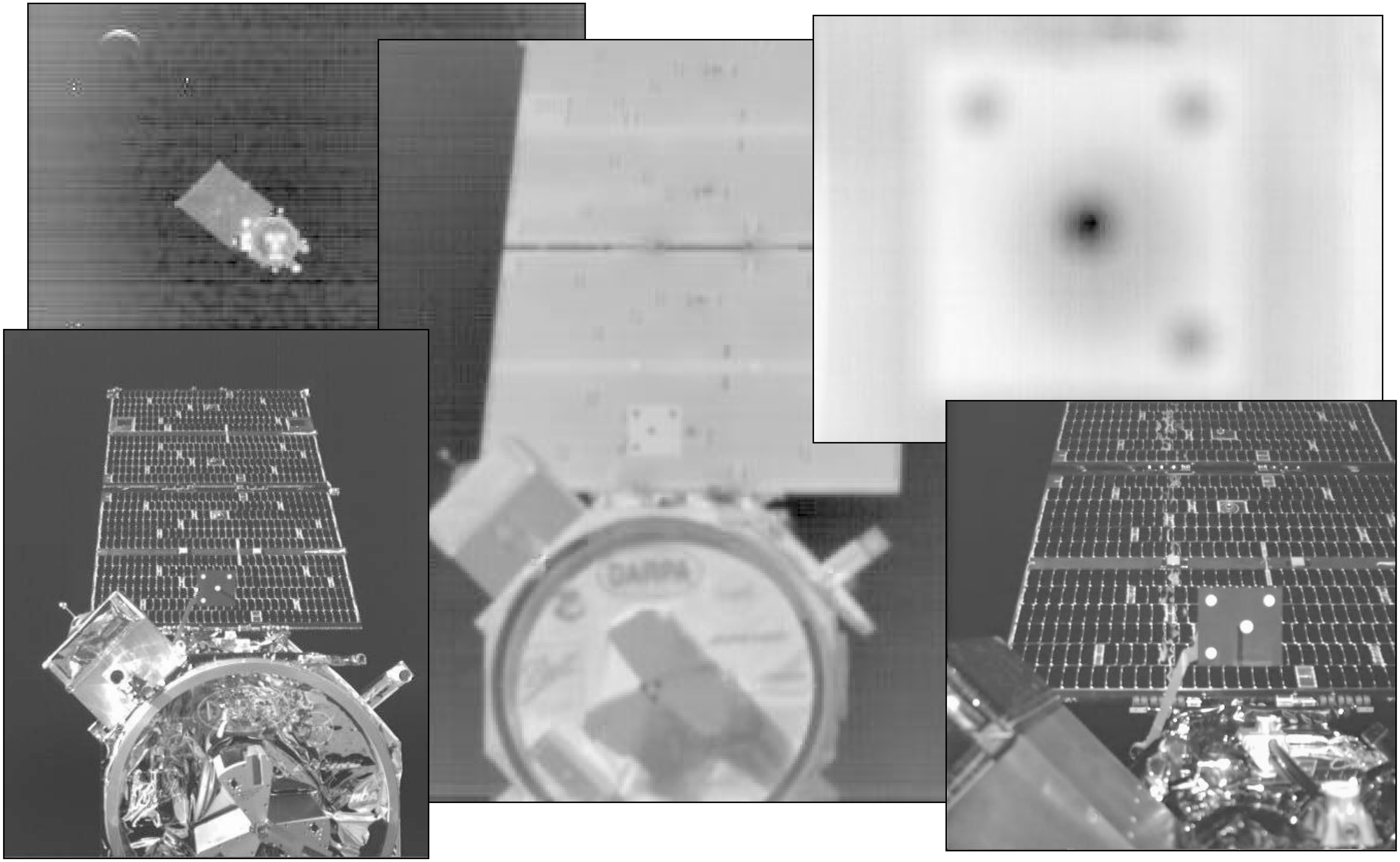


Scenario 3-1 Recovery (cont'd)

- Exact orbit dimensions unknown, so ground allowed ASTRO to coast ahead of NEXTSat
  - No sensor tracking
  - Apogee above, perigee below, some out-of-plane
- ASTRO coasted to approx. +6 km, then ground commanded posigrade correction burn to null opening rate
- Over several days, ground iterated on sensor & Kalman filter inputs
  - Learned a great deal, given true imaging environment
  - Bad data incorporated into nav filter not a problem, since ASTRO coasting
  - Occasional ground updates of NEXTSat state vector reset nav filter
- Ground commanded burns to close on NEXTSat
- IR Camera tracking & laser track established
- Ground loaded new guidance inputs ending in successful AR&C (direct capture)
  - IR Camera track 3km to mate
  - LRF track inside 2.5 km
  - AVGS track inside 150 m
- Improved ground understanding of relative navigation system behavior



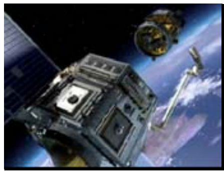
AR&C Exercise #2 Photos



Scenario 5-1

(Return to Unmated Operations)

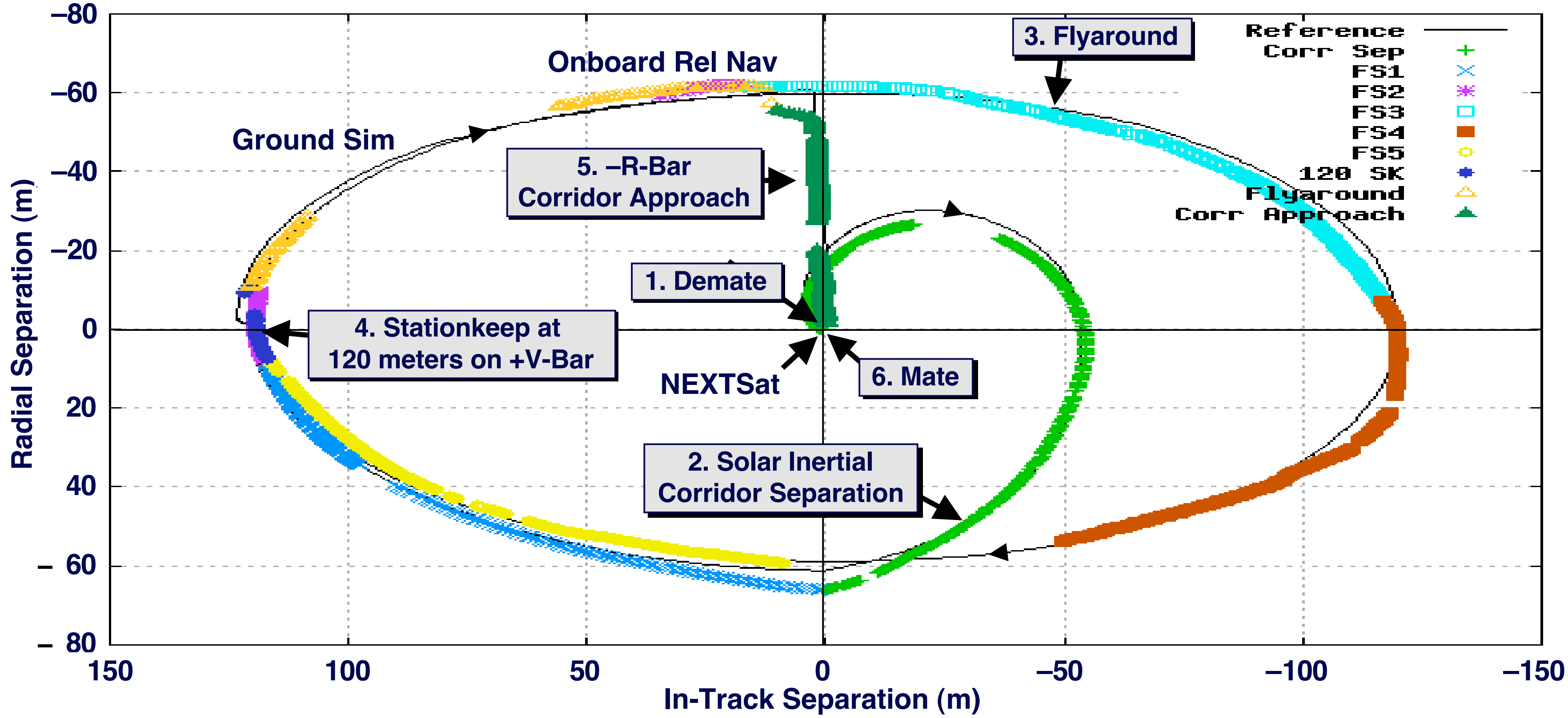
16 June 2007 (UTC)



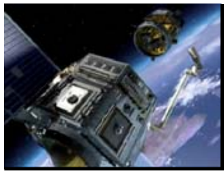
Scenario 5 Plan

- Scenario 5 consisted of a single unmated operation
  - No planned battery or propellant transfers
- Max range = 120 m, -R bar approach
- Unmated for $4^{h}\ 46^{m}\ 54^{s}$ within $\pm 5^{m}$
  - Daylight demate over LION with sun _=–3.3°
  - Solar inertial separation to 70 m below/right of NEXTSat
  - Large 47 m crosstrack
  - ±120x60 m elliptical flyaround
    - Natural motion with correction burns as needed
    - Single-orbit rate
  - +120 m stationkeep
  - Daylight mate over TDRSS with _=–2.6°
- Sensor redundancy
  - Vis-STAR track entire time
  - AVGS track during corridor separation & approach
- Direct capture

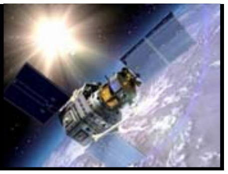
Scenario 5-1
Planned & Actual In-Plane Trajectories



Scenario 5 Onboard-Computed Trajectory Matched Ground Simulation Very Well

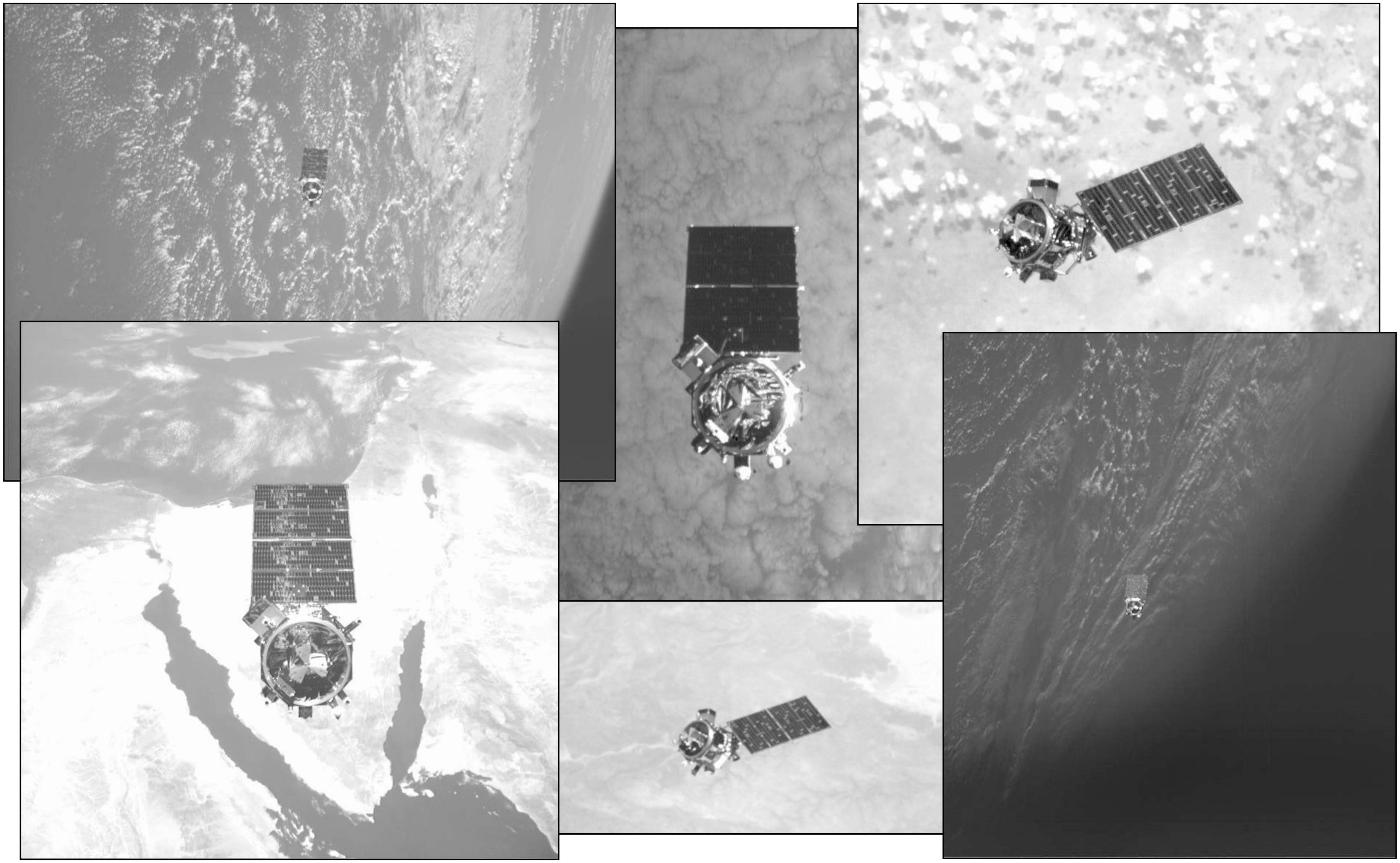


Scenario 5-1 Results



- Max range = 120 m
- Unmated for $4^h\ 51^m\ 7^s$
  - Demate (UTC): June 16th at $9^h\ 47^m\ 2^s$
  - Capture initiation: June 16th at $14^h\ 36^m\ 22^s$
  - Mate: June 16th at $14^h\ 38^m\ 9^s$
- Fully autonomous, flawless execution
- Excellent sensor performance
  - Nearly-continuous Vis-STAR tracking during all phases & lighting conditions, including earth background
  - Laser rangefinder near 100% accurate returns while beyond 50 m
  - AVGS near-continuous track while within 27° alignment (98 m outbound)
- GN&C and thrusters behaved nominally (no overheating)
- Batteries remained mostly charged despite LVLH approach
- NEXTSat properly held solar inertial & LVLH attitudes
- Improved ground understanding of relative navigation settings

AR&C Exercise #3 Photos

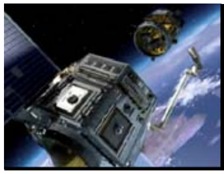


BOEING

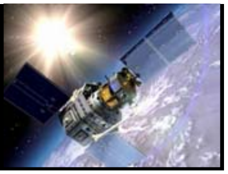
Scenario 7

(Unmated Operation to 4km)

23 June 2007 (UTC)

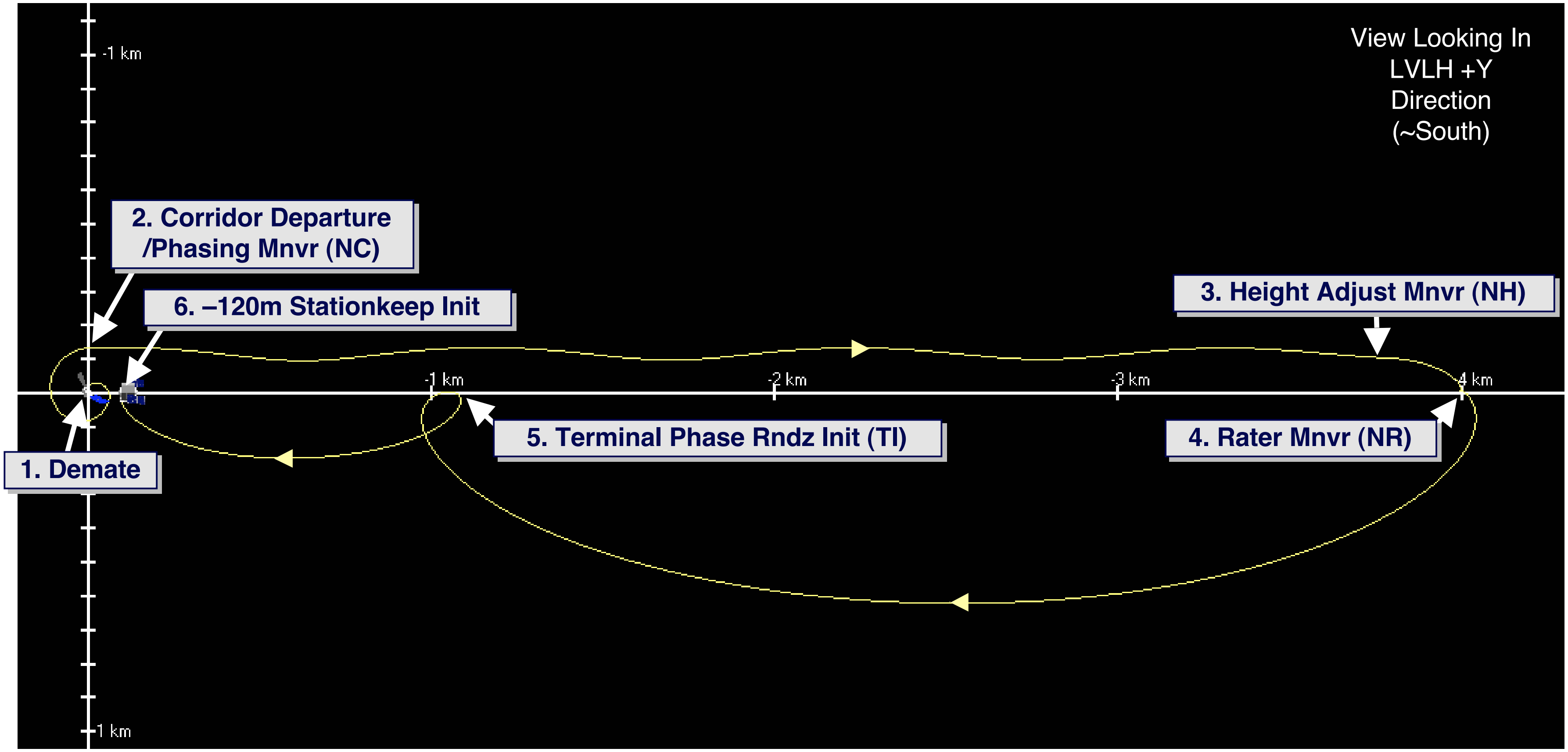


Scenario 7 Plan

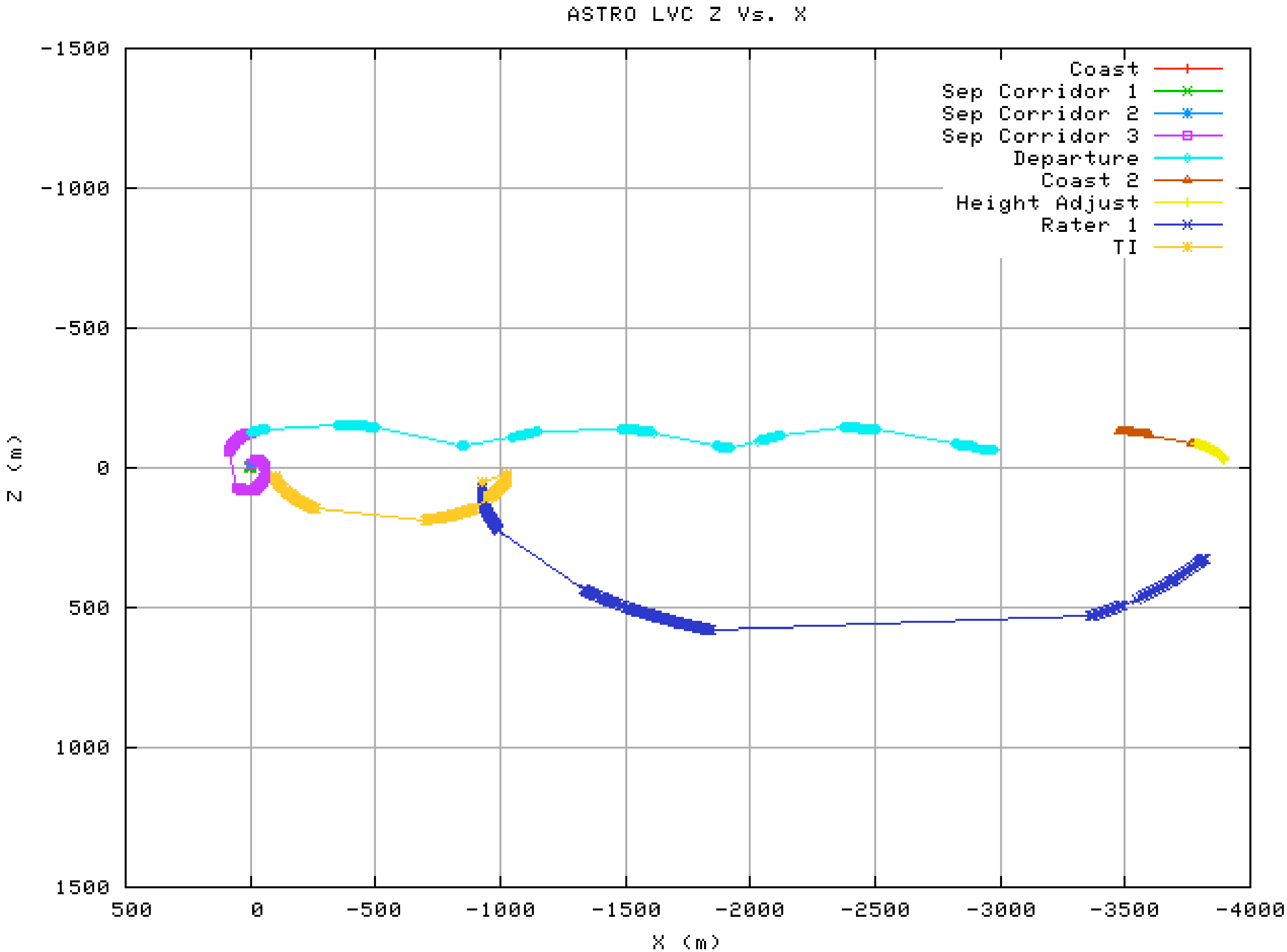


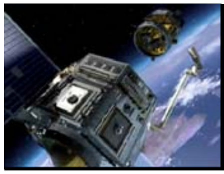
- Max range = 4 km
- Unmated for $16^h\ 45^m\ 59^s$ within $\pm 5^m$
  - Daylight demate over GUAM
  - Solar inertial separation to 130 m above NEXTSat
  - Phasing to –4 km (behind NEXTSat)
  - Return to –120 m v-bar stationkeep
  - 100 m near-circular flyaround
    - Forced-motion, in-plane inspection
    - Single-orbit rate
  - +120 m v-bar stationkeep
  - Transfer to 60 m corridor
  - Solar inertial approach
- First autonomous robotic grapple & berth (Free Flyer Capture)
  - Night pass over REEF or TDRSS

Scenario 7
Planned In-Plane Rendezvous Trajectory

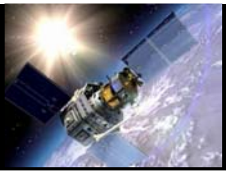


Scenario 7
Onboard In-Plane Rendezvous Trajectory



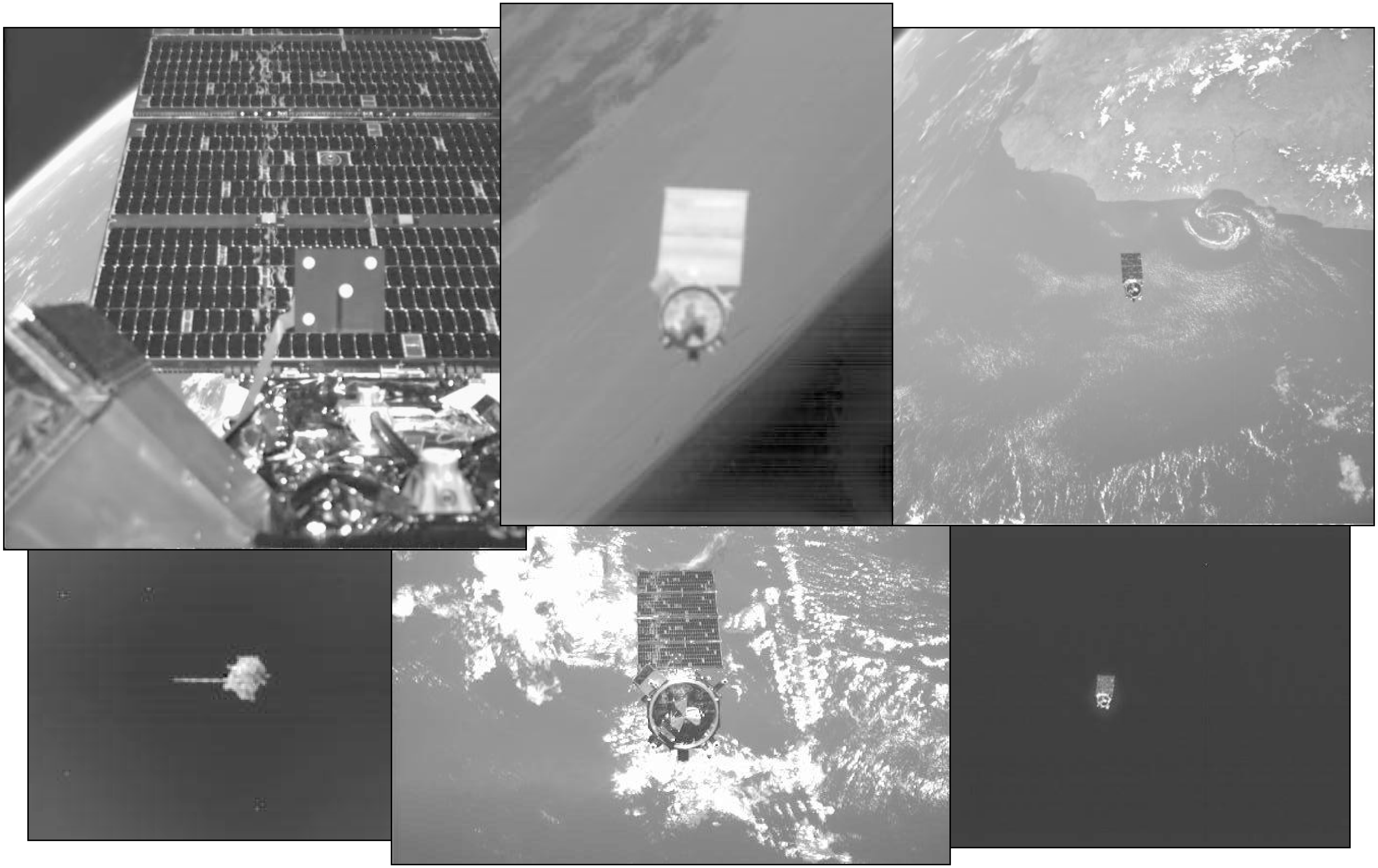


Scenario 7 Results



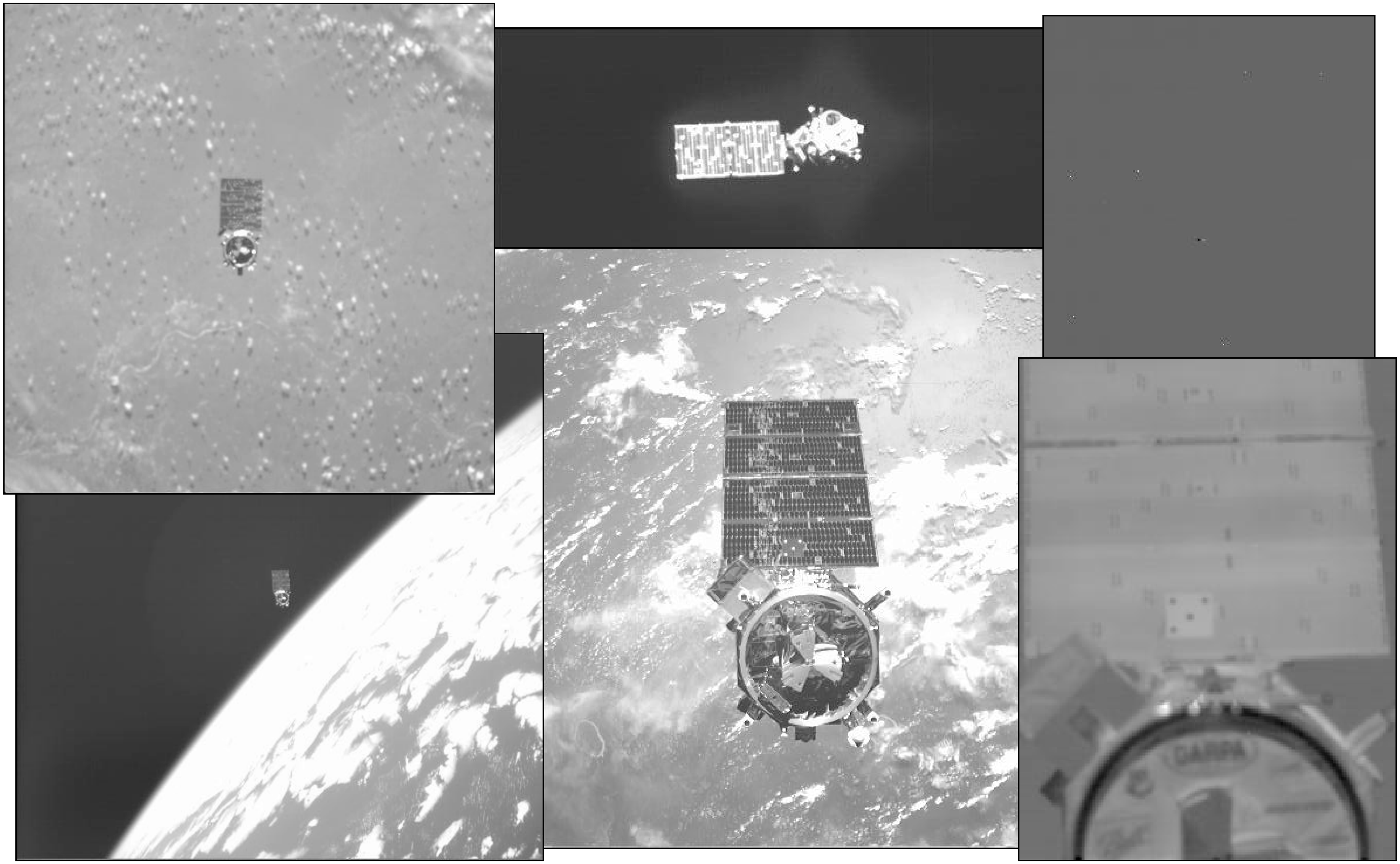
- Max range = 4 km
- Unmated for $22^{h}\ 2^{m}\ 19^{s}$
  - Demate (UTC): June 23th at $0^{h}\ 55^{m}\ 42^{s}$
  - Grapple initiation: June 23th at $17^{h}\ 37^{m}\ 38^{s}$
  - Mate: June 23th at $22^{h}\ 58^{m}\ 1^{s}$
- Fully autonomous, flawless rendezvous & prox ops
- World’s first autonomous grapple
- Autonomous berth stopped by onboard mission manager
  - Script error
  - Completed with ground assistance

Scenario 7 Photos



BOEING

AR&C Exercise #4 Photos



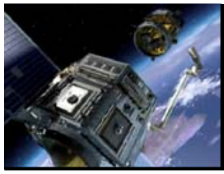
Scenario 8

(Design Reference Mission)

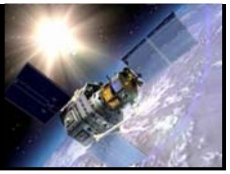
27-29 June 2007 (UTC)

Scenario 8 Description

- Scenario 8-2 was the Design Reference Mission
  - Depart to 7km
  - Return & perform free flyer capture,
  - Battery transfer to ASTRO
  - Battery & propellant transfer to NextSat
  - Discretely execute sensor computer (AC3) transfer
- Departure and return from -7km completed without incident
  - Grapple anomaly after successful capture
  - Ground had to intervene once ASTRO safed the system
  - Once back into configuration Scenario Resume command was executed and remaining battery and propellant transfers went without incident
- Computer transfer completed successfully
  - Ground intervention required

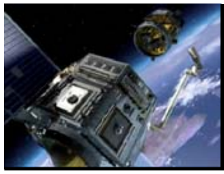


Scenario 8-2 Plan

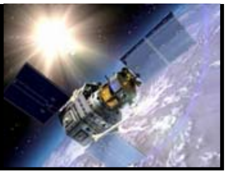


- θ Max range = 7 km
- θ Unmated for $1^{d}\ 1^{h}\ 25^{m}\ 45^{s}$ within $\pm 5^{m}$
  - _ Demate at night with sun _=44.0°
  - _ Solar inertial separation to 78 m above and slightly left of NEXTSat
  - _ Phasing to –7 km (behind NEXTSat)
  - _ Return to –4 km followed by demonstration of standoff mode for ~$6^{h}43^{m}32^{s}$
  - _ Return to –120 m v-bar stationkeep for
  - _ 100 m near-circular inspection flyaround at 3 times orbital rate
  - _ +120 m v-bar stationkeep
  - _ Transfer to 60 m corridor and solar inertial approach
  - _ Night grapple & berth over HULA within $\pm 5^{m}$ with _=48.6°
- θ Vis-STAR track entire time
- θ AVGS track during separation and approach

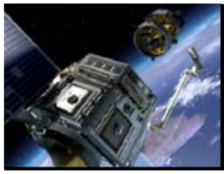
BOEING



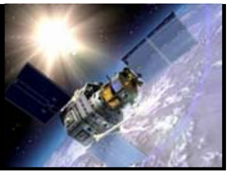
Scenario 8-2 Results

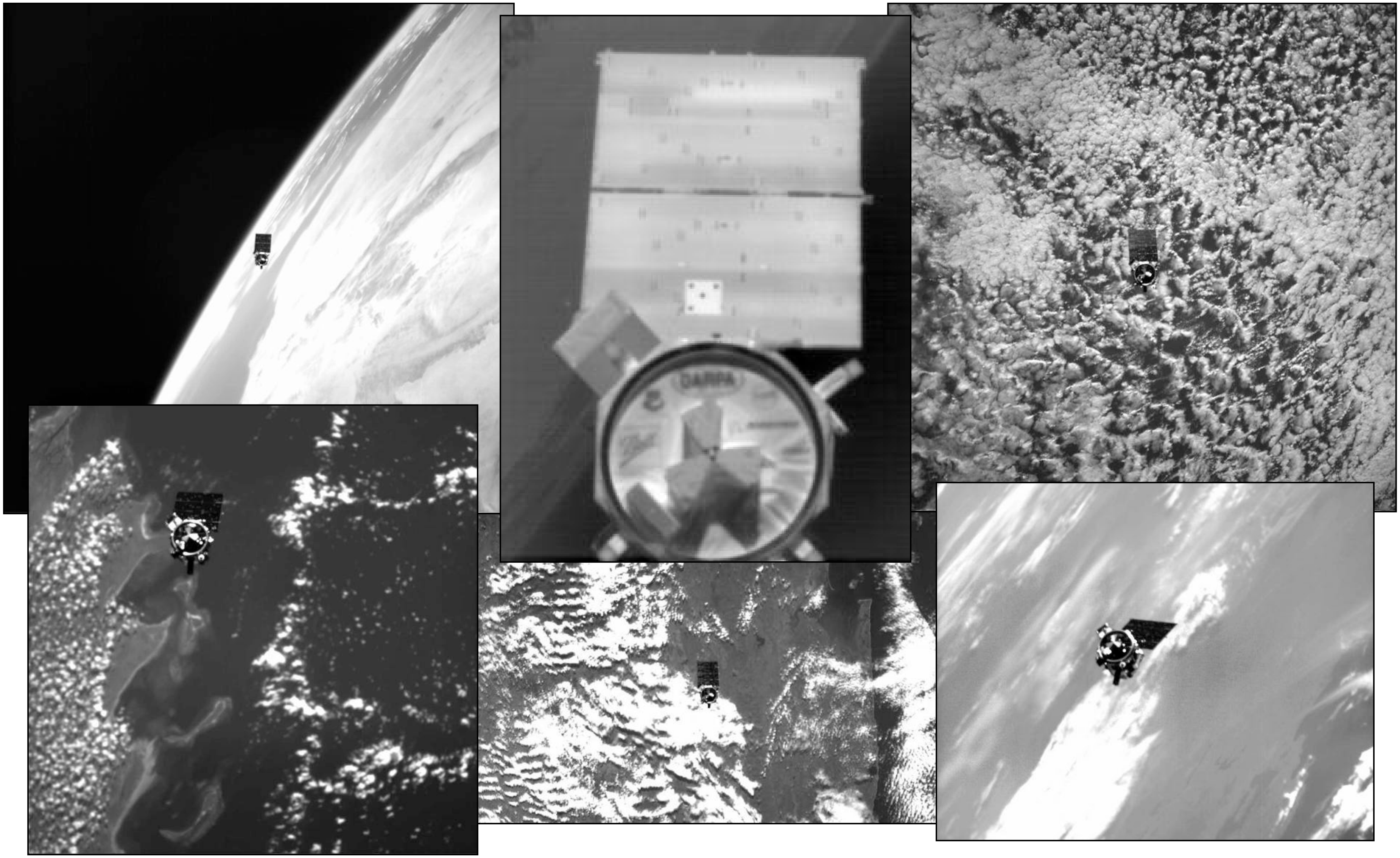


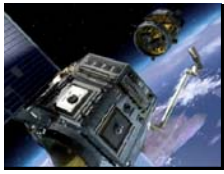
- Max range = 7 km
- Unmated for $1^{d}\ 21^{h}\ 54^{m}\ 19^{s}$
  - Demate (UTC): June 27th at $8^{h}\ 9^{m}\ 13^{s}$
  - Grapple initiation: June 28th at $9^{h}\ 31^{m}\ 55^{s}$
  - Mate: June 29th at $6^{h}\ 3^{m}\ 32^{s}$
- Fully autonomous, flawless rendezvous & prox ops
- Grapple anomaly
  - Late trigger of end effector “mousetrap”
  - Ground commanding required to berth NEXTSat



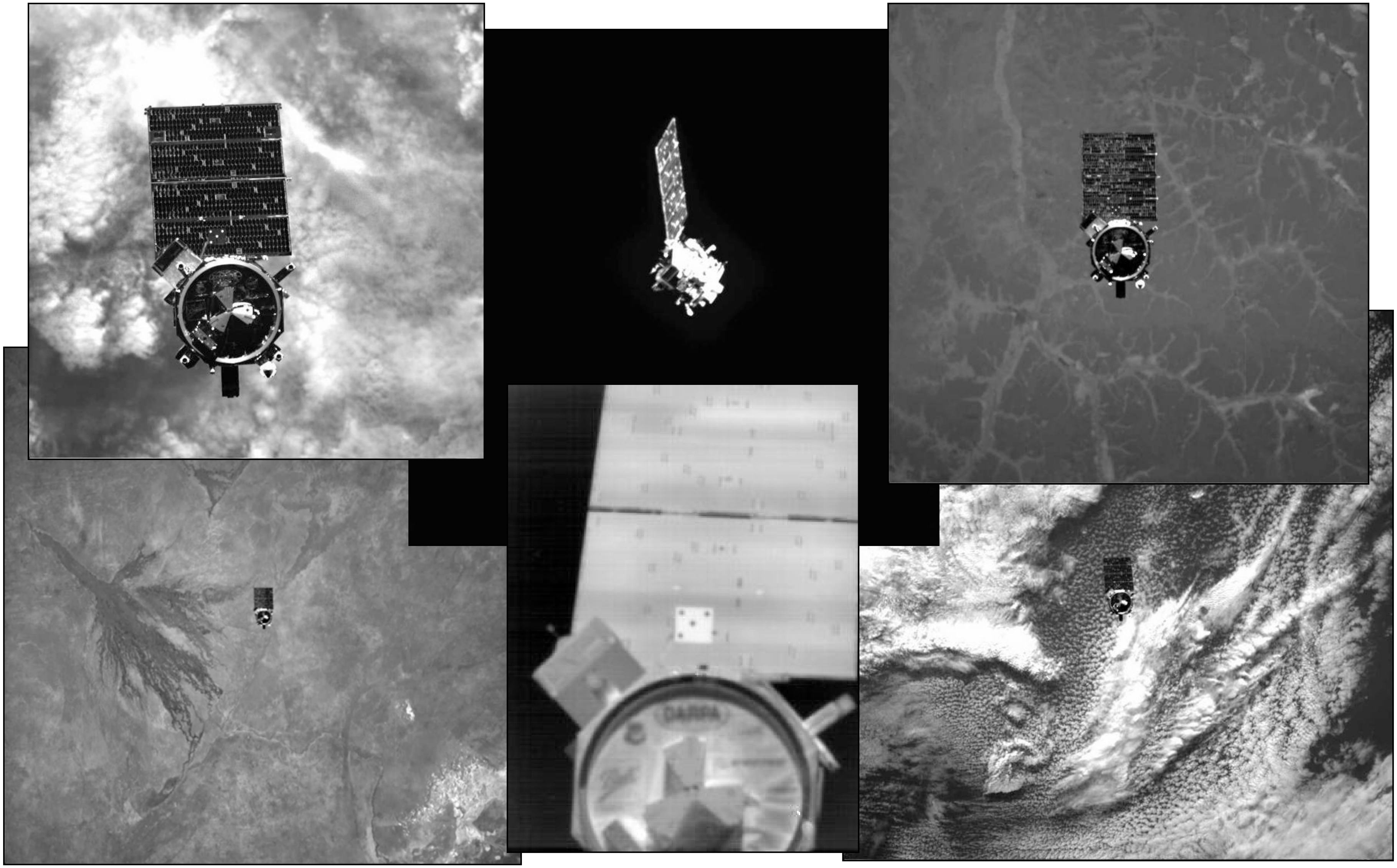
AR&C Exercise #5 Photos



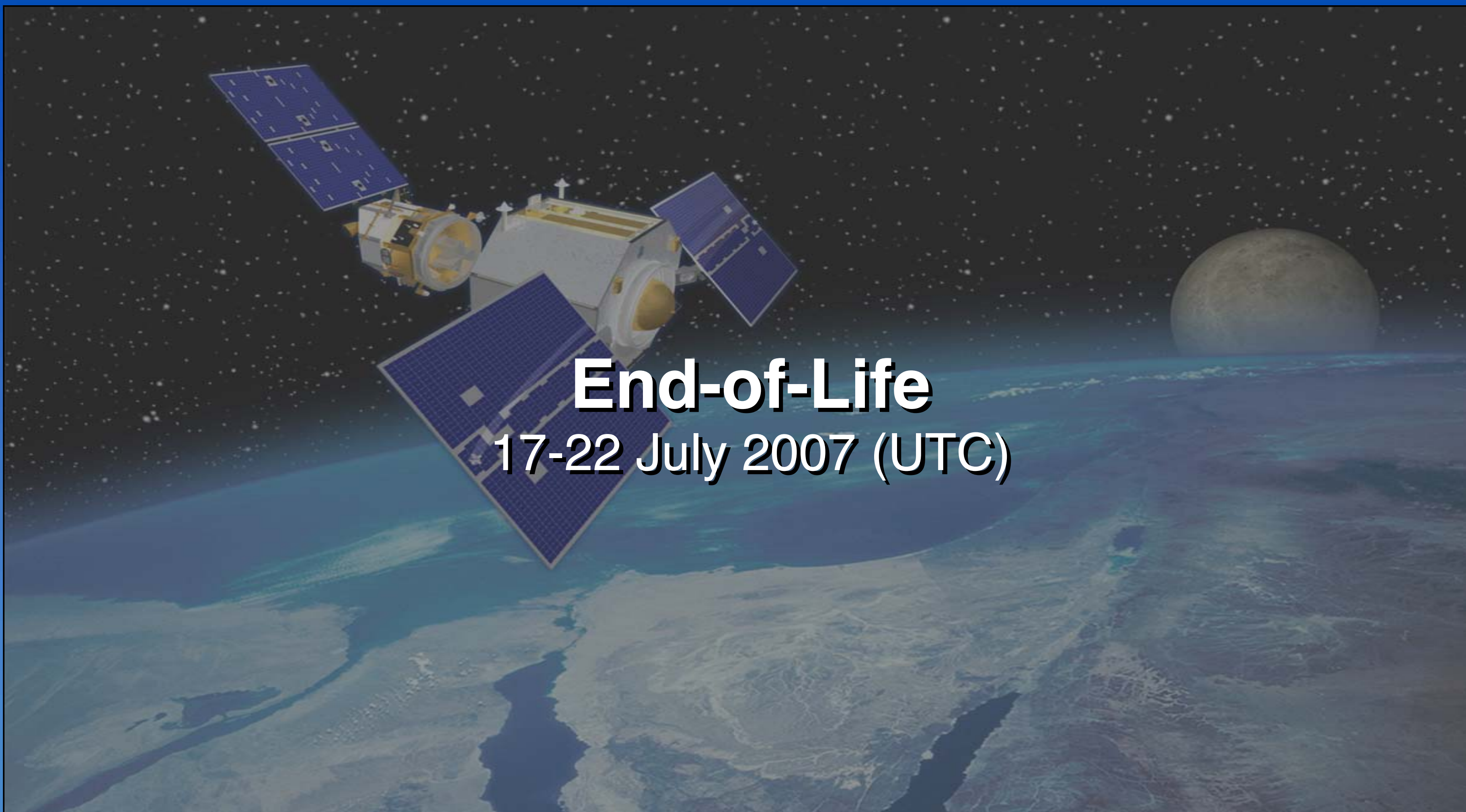




AR&C Exercise #5 Photos

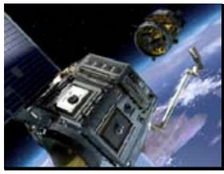


BOEING



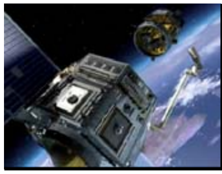
End-of-Life

17-22 July 2007 (UTC)



End-of-Life Exercise Plan

- Perform departure to 200km and return to 1km
  - Demate July 17th and depart to 200km
  - Return and Hold in Racetrack at 1km for 24 hours, then depart to 1000km
  - Complete propellant depletion operations and end of life July 20th
- Final tests of autonomous rendezvous systems
- Final state unmated, never to re-contact again
  - Unmated state chosen by DARPA to meet ground casualty risk criteria
- Both spacecraft to de-orbit within 25 yrs
  - NEXTSat: 2.1 to 5.8 yrs
  - ASTRO: 4.6 to 21.4 yrs



End-of-Life Exercise Results

- Demate (UTC): July 17th at $3^{h}\ 41^{m}\ 0^{s}$
- During departure to 200km DARPA direction received to depart until sensor contact with NextSat was lost
  - Load client state vector from ground supplied data
  - Return and perform standoff at 1km prior to executing final departure
- Flawless transfer to –410 km, return to 1 km
  - Flawless standoff between –1 km & –500 m (4 laps around “racetrack”)
    - Unrecoverable laser rangefinder failure
    - IR camera provided sufficient angles data
  - Flawless transfer to 15 km above NEXTSat, drifting behind
  - Input “corkscrew” for additional safety (1.25 km crosstrack injected)
- Unmated inside 1000 km for $3^{d}\ 4^{h}\ 36^{m}\ 0^{s}$
  - – 1000 km outbound: July 20th at $8^{h}\ 7^{m}\ 0^{s}$
- Remaining fuel depleted prior to ASTRO permanent shutdown
  - Depletion required 2 days
- ASTRO Decommissioned 7/22/07
  - NextSat Decommissioned 7/19/07